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Assessment of the relationship between earthquakes and volcanic activity

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Assessment of the Relationship Between Earthquakes and Volcanic Activity

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Abstract

Understanding precursors to natural hazards is critical if we are to optimise emergency planning and reduce the impact of natural disasters when they strike. At present, the relationship between earthquakes and volcanoes provides vital clues for volcanic activity prediction and the identification of precursors. Despite this, there is currently no clear evidence supporting a mechanism of response. By extending the work of previous studies, this research makes a contribution to the field of volcanic hazard assessments by investigating the relationship between regional earthquakes and volcanic activity. Previously, it was difficult to measure the level and nature of volcanic activity given the inherent threat posed by volcanic hazards. As a result, there is an abundance of research that investigates the relationship using historic or observational records despite these methods presenting a number of limitations. For this reason, the advent of satellite remote sensing for volcanology has provided an opportunity to monitor long-term activity and quantify changes in a volcano's character. Using data from the MODIS sensor (MOD14 and MODVOLC), the radiative power of a volcano was cross-checked with global seismic records to examine the thermal response of volcanoes to regional earthquakes. While preliminary results identified increases in radiative power up to 50 days after an earthquake, more detailed analyses between variables (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance) found no statistically significant relationships. In contrast, spatial analyses corresponded with previous research which proposed mechanisms of response based on physical interactions. With this in mind, further work could examine individual earthquake-volcano interactions to identify a set of common factors which define the relationship, ultimately improving volcanic hazard assessment and response.

Keywords: Earthquakes, Volcanoes, Relationship, Volcanic Hazard Assessments, Remote Sensing

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Chapter 1

Introduction

1.1 Introduction

Natural hazards are phenomena which have the potential to cause widespread damage and loss (Alexander 2001; UNEP 2012). Despite their inherent risk, a disaster is only declared when the ability of a society to cope using its own resources are exceeded (Alexander 2001; UNEP 2012). With the increasing risk posed by natural hazards (Figure 1.1), the identification of potential precursors is critical in order to optimise emergency planning and reduce the impact of natural disasters when they strike (Alexander 2001; Tralli *et al.* 2005; Huppert and Sparks 2006). In particular, major geological hazards, such as earthquakes and volcanoes, have killed more than 800,000 people (since 1990) and remain some of the most difficult hazards to predict (Huppert and Sparks 2006; EM-DAT 2012a).

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Figure 1.1 Increasing number of natural disasters reported 1900-2011, black line indicates the average trend (Source: EM-DAT 2012b).

Satellite remote sensing offers the potential to monitor natural hazards from afar and by integrating such data with the emerging body of geo-data it is possible to identify long-term activity and characterise precursors. For example, the integration of seismic datasets with space-based GPS (Global Positioning Systems) measurements are enabling planners to model earth surface processes and estimate future earthquakes (Tralli *et al.* 2005). Equally, there is a need to limit the number of 'suggested' precursors causing false alarms and presenting problems for forecasting and mitigation (Huppert and Sparks 2006). Such an example is discussed by Blackett *et al.* (2011) who has shown that the hypothetical relationship between thermal anomalies and earthquakes does not stand up to rigorous analysis. By falsifying this hypothesis Blackett *et al.* (2011) hoped to limit the misuse of thermal anomalies to inadvertently declare civil emergencies following a 'false positive' observation. This thesis aims to make a similar contribution to the field of volcanic hazard assessments by investigating the proposed relationship between earthquakes and volcanoes.

1.2 Geological Hazards

Earthquakes and volcanoes are both recognised to be manifestations of tectonic activity (Linde and Sacks 1998). Most often occurring along plate boundaries, volcanoes form at the earth's crust and act as a chamber in which magma collects until a change in conditions initiates an eruption (Coch 1995; Alexander 2001; Christopherson 2006). This process is most often associated with changes in pressure resulting from an influx of magma or a change in stress and are capable of causing a number of hazards which include lahars, ash clouds and lava flows (Alexander 2001; Bryant 2005; Magna and Brodsky 2006; Walter 2007).

In contrast, earthquakes occur when the strain that exists at the boundary between two plates is released (Selva *et al.* 2004; Christopherson 2006). The energy released by this rupture then travels in waves across the earth's surface which is felt as an earthquake (Coch 1995). The strongest earthquakes, $M \geq 7.0$, are normally related to the dissipation of seismic waves from active plate margins and are capable of causing widespread damage and loss of life (Stein 1999; Udias 1999; Freed 2005). Alongside this, earthquakes are also capable of initiating a number of secondary hazards (landslides, tsunamis, liquefaction), and it is here that the influence of earthquakes on volcanic activity is increasingly discussed (Linde and Sacks 1998; Hill *et al.* 2002; Walter and Amelung 2007).

1.3 Earthquake-Volcano Interactions

Spatially, early recognitions of a link between earthquakes and volcanoes resulted from their locations along convergent plate boundaries. However, with the increasing significance of earthquakes and volcanoes and their high number of co-occurrences, the possible relationship between regional earthquakes and volcanic activity may have serious implications for the identification of precursors, hazard assessment and early warning (Linde and Sacks 1998; Hill *et al.* 2002; Magna and Brodsky 2006; Walter 2007; Eggert and Walter 2009). In particular, the two-way coupling between earthquakes and volcanoes has been the subject of debate for many years. Indeed, their complimentary nature suggests that an equilibrium exists whereby magma movement may cause instability triggering an earthquake and, conversely, a change in stress (resulting from an earthquake) may initiate an eruption (Nostro *et al.*1998; Moran *et al.* 2002; Eggert and Walter 2009).

In terms of the effect of volcanic activity on earthquakes, the most widely recognised pattern is a period of increased volcanic activity prior to an earthquake (Carr 1977; Kimura 1976; Acharya 1982; Thatcher and Savage 1982; Acharya 1987). In particular, instances of volcano-earthquake triggering have been noted in Hawaii (Walter and Amelung 2004), Italy (Gresta *et al.* 2005) and Japan (Kimura 1976; Alam *et al.* 2010). Yet despite these clear examples, less attention has been given to the effect of volcanic activity on earthquakes due to the potential benefits for volcanic activity prediction.

Globally, it is well known that volcanoes have a number of precursory signals prior to the onset of an eruption (McNutt 1996; Chastin and Main 2003). In particular, volcanic seismicity is recognised as a precursory indicator of renewed activity and is thought to reflect magma movement and unrest (Brodsky *et al.* 1998; Marzocchi *et al.* 2002; Collombet *et al.* 2003). Alongside this, emerging evidence supports the effect of regional earthquakes on volcanic activity. Notably, reports of regional earthquakes triggering volcanic activity date as far back as 1840 when Darwin (1840) reported volcanic activity in Chile following an earthquake and in 1903 when Rockstroh (1903) reported an eruption following a M8.3 earthquake in Guatemala. More recently, in the days following the M7.4 earthquake in Mexico (March 2012), triggered seismicity at San Salvador volcano was recorded (Volcano Discovery 2012). A month later, volcanic activity at Popocatepetl (275 km away) was also reported (USA Today 2012). Although convincing, these reports were opportunistic and, as a result, failed to determine the direct effect of these earthquakes on volcanic activity. The advent of satellite remote sensing for volcanology has therefore provided researchers with an opportunity to support systematic studies of the relationship. In particular, thermal remote sensing provides an opportunity to quantify the timing, magnitude and character of volcanic events and by integrating this data with the global archive of seismic data it is possible to identify the response of volcanoes to earthquakes (Harris and Ripepe 2007; Delle Donne *et al.* 2010).

1.4 Remote Sensing Technologies

Previously, it was difficult to measure the level and nature of volcanic activity using ground based instruments. For this reason, the advent of satellite remote sensing for volcanology offers a crucial application to monitor volcanoes from afar (Gawarecki *et al.* 1965; NASA Earth Observatory 2004). Firstly, the ability of sensors to monitor volcanoes at a global scale has enabled spatially continuous, near real-time imagery to be collected on volcanoes that have poor monitoring equipment or volcanoes that are located in particularly remote areas (Wright *et al.* 2004; Tralli *et al.* 2005). More importantly, collection of satellite imagery at varying resolutions has enabled a range of datasets to be collected which contribute towards the understanding of tectonic movements and volcanic hazards (Tralli *et al.* 2005). Finally, the ability to combine this data with numerical models and in-situ measurements means it is possible to identify and characterise volcanic precursors (McNutt 2002).

1.5 Global Seismic Networks

Equally, the provision of a global seismic record of earthquakes since the 19th Century has provided researchers with a platform to increase their scientific knowledge and understanding of earth sciences (USGS 2012a). Currently, the United States Geological Survey, National Earthquake Information Centre (USGS NEIC) offers the potential to quantify the location, magnitude and timing of earthquakes. In particular, the application of these datasets has provided a number of advantages which have contributed to the monitoring of tectonic hazards (Stein 1999; Freed 2005).

1.6 Research Aims and Objectives

This study will employ remote sensing to assess the thermal response of volcanoes (a proxy for volcanic activity) to regional earthquakes (large ($M \geq 4.5$) seismic events within

1000 km of a volcano). Firstly, this research will re-examine previous work by Delle Donne *et al.* (2010). An extended method will then be set out in an attempt to identify regional earthquakes as a precursory indicator to volcanic activity. Overall, this thesis aims to determine the statistical significance of the potential relationship between earthquakes and volcanoes. As such, the methodology will be divided into 2 phases and will be met by the following objectives:

- To contextualise the current state of understanding of earthquake-volcano interactions by conducting a comprehensive review of literature.
- To re-examine previous work by Delle Donne *et al.* (2010) who found statistically significant results using remotely sensed data.
- To generate a set of recommendations that will be incorporated into an extended method.
- To investigate statistical and spatial relationships between regional earthquakes and volcanic heat anomalies using seismic and volcanic datasets.
- To propose mechanisms of response through the evaluation of statistical and spatial relationships.

1.7 Conclusion and Research Structure

This chapter has introduced the principles of natural hazards and satellite remote sensing, as well as identifying the aims and objectives of this thesis. Due to the nature of this research, this thesis will be divided into 2 phases in which recommendations from the pilot study will be incorporated into an extended method. As such, this thesis will be set out in the following structure. Firstly, a comprehensive review of literature will establish the current state of understanding of earthquake-volcano interactions and identify the contribution of this research to the field (Chapter 2). Chapter 3 will then outline data sources and dataset properties as well as discussing each method individually. Based on this, the results of each method will be presented and analysed (Chapter 4). Finally, Chapters 5 and 6 will discuss the findings of this research in relation to the literature and conclude by summarising the key findings and implications of this research, as well as identifying further research needs.

Chapter 2

Literature Review

The scientific principles of natural hazards and satellite remote sensing were introduced in Chapter 1. This chapter establishes the current state of understanding of the relationship between earthquakes and volcanoes, exemplifies the use of remote sensing to characterise volcanic activity and identifies the use of these applications to earthquake-volcano studies. In addition, modelling and forecasting approaches will be reviewed in order to identify the contribution that this research could have on the prediction of volcanic activity following earthquakes.

2.1 The Relationship between Earthquakes and Volcanic Activity

The relationship between earthquakes and volcanoes has attracted considerable interest over many years. Despite resulting from a number of anecdotal records (detailed in Section 1.3), this possible relationship has gained particular attention in recent decades primarily resulting from an increased awareness of and need to understand natural hazards (Alam *et al.* 2010). One of the first studies to provide evidence of the relationship was MacGregor (1949). Focusing on the Caribbean volcanic arc, earthquake-volcano interactions were recorded and it was suggested that future occurrences could be forecast on the basis of these patterns. More recently, Latter (1971) and Carr (1977) investigated the potential relationship between earthquakes and volcanoes. In these papers, large earthquakes ($M \geq 6.0$ and $M \geq 7.5$, respectively) were examined alongside volcanic datasets to identify patterns of response which can be attributed to these possible interactions. Further extension to the work of Carr (1977) by Acharya (1982) noted that this complex relationship appears to be dependent on the magnitude of the earthquake. Overall, the synopsis of this early work indicated that tectonic stresses can be attributed to the interactions between earthquakes and volcanoes (Latter 1971; Nakamura 1977).

More recent assessments have recognised the need to conduct statistical analyses of this relationship at the global scale (Linde and Sacks 1998; Hill *et al.* 2002; Marzocchi 2002; Marzocchi *et al.* 2004; Magna and Brodsky 2006; Eggert and Walter 2009). Perhaps one of the most noted papers is Linde and Sacks (1998). Motivated by the triggered seismicity of Long Valley Caldera to the 1992 Landers earthquake, this research was one of the first statistical analyses that found increases in volcanic eruptions directly following an earthquake. They associated these increases in volcanic activity with complex tectonic interactions between earthquakes and volcanoes, concluding that they were most likely due to the propagation of seismic waves. At the same time, Brodsky *et al.* (1998) proposed a mechanism of rectified diffusion for this relationship, suggesting that dynamic strain resulting from regional earthquakes are the probable cause of activity at volcanoes that were already in a critical state.

Subsequently, Hill *et al.* (2002) speculated the nature of this relationship at different spatial scales. By focusing their research on the emerging evidence of earthquake-volcano interactions, Hill *et al.* (2002) attempted to identify precursors to volcanic activity. Overall, it was concluded that stress changes resulting from large earthquakes were the most likely trigger of volcanic activity, further confirming the argument of Linde and Sacks (1998). Coinciding with this, Marzocchi (2002); Marzocchi *et al.* (2002) and Marzocchi *et al.* (2004) demonstrated the role of stress changes in the coupling of these two hazards. In addition, Marzocchi *et al.* (2004) computed a histogram which identified a spatial range of up to 900 km for occurrences with the strongest couplings (Figure 2.1). Once again, conclusions were drawn that identified a statistically significant relationship as well as suggesting that previous studies which identified dynamic stress changes as the trigger are appropriate.

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Figure 2.1 Histogram of spatial range between earthquakes and volcanoes with the strongest coupling ranging from 0–900 km (Source: Marzocchi *et al.* 2004: 3).

Additional examples that have investigated the relationship at a global scale include Magna and Brodsky (2006); Lemarchand and Grasso (2007) and Eggert and Walter (2009). While Magna and Brodsky (2006) examine the role that stress variations have on volcanic eruptions, Lemarchand and Grasso (2007) mirror the methodology of Linde and Sacks (1998) to conduct a spatial and temporal investigation of the proposed relationship. Additionally, Eggert and Walter (2009) provided evidence of a statistically significant relationship between the two-way coupling of earthquakes and volcanoes. Most notably, the latter study added that a period of volcanic silence is experienced prior to an earthquake, a finding that was also noted in earlier work by Carr (1977).

More localised investigations have been conducted to examine the occurrence of this relationship at a regional scale (Barrientos 1994; Moran *et al.* 2002; Alam and Kimura 2004; Walter 2007; Watt *et al.* 2009; De Le Cruz-Reyna *et al.* 2010; Yamazaki *et al.* 2011). Firstly, Italy is recognised as an area which is particularly vulnerable to seismic and volcanic hazards and has a number of speculative couplings. At around the same time as Linde and Sacks (1998), Nostro *et al.* (1998) conducted statistical analyses of the two-way coupling between regional earthquakes and volcanic eruptions at Vesuvius. In particular, it was noted that earthquakes in this region generally precede volcanic eruptions by up to 6 years, promoting activity due to stress changes acting on the magma chamber. Further studies in this region have also confirmed similar stress triggers at Mount Etna (Gresta *et al.* 2005; Walter *et al.* 2009), Stromboli (Cigolini *et al.* 2007; Walter *et al.* 2009) and Panarea (Walter *et al.* 2009). Additionally, unrest at 3 volcanic centres following a M5.9 earthquake demonstrated a spatial pattern of response (Figure 2.2) (Walter *et al.* 2009). For this occurrence, all volcanoes flagged as responding are located to the South and East of the earthquake epicentre.

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Figure 2.2 Spatial pattern of responding volcanoes (red triangles) to the M5.9 Palermo earthquake (red star) (Source: Walter *et al.* 2009: 16).

Recently, large earthquakes (M≥8.8) in Indonesia (2004), Chile (2010) and Japan (2011) indicated their effect on arc-wide volcanic activity. The 2004 Boxing Day earthquake, in particular, has attracted considerable interest (Selva *et al.* 2004; Walter and Amelung 2007; Walter *et al.* 2007; Alam *et al.* 2010). For example, following the M9.3 event, Walter and Amelung (2007) suggested a mechanism of stress transfer in which earthquake-induced decompression of the magma chamber promoted the eruption of two volcanoes (Figure 2.3d). In addition, volcanic activity at Merapi has been noted following smaller magnitude events, Figure 2.4 (Walter *et al.* 2007). Of particular relevance, this study implied that dynamic stress changes resulting from an earthquake are the main influence on a response (Walter *et al.* 2007).

Figure 2.3 Examples of earthquake-volcano interactions: (D) shows Sumatra-Andaman M9.3 earthquake. Volcanoes shown by red triangle indicate volcanoes that have erupted within 3 years of the earthquake. Notably, Barren Island began to erupt on the 28th May 2005, 5 months after the M9.3 Boxing Day earthquake and 2 months after a M8.7 earthquake (Source: Walter and Amelung 2007: 539).

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Figure 2.4 Volcanic activity changes at Merapi (a) shows temperature increase following the 2001 M6.3 earthquake and, (b) shows increase in pyroclastic avalanches following the 2006 M6.3 earthquake; red arrows indicate earthquake occurrence (Source: Walter *et al.* 2007: 2).

Persistent seismic activity in Japan has also prompted research in this region. Work by Alam and Kimura (2004) and Alam *et al.* (2010) found that the relationship is closely related to changes in stress resulting from tectonic movement. Furthermore, Wang *et al.* (2011) and Yamazaki *et al.* (2011) noted the eruption of Shinmoedake two days after the 2011 M9.0 earthquake. By studying variations in the stress field, Wang *et al.* (2011) suggested that increased activity at Mount Fuji and Changbaishan was also possible.

Similarly, it is well known that within South America seismic and volcanic hazards pose a large threat. This zone of activity results from the subduction of the Nazca Plate beneath the South American Plate (Dzierma and Wehrmann 2010). The early work of Barrientos (1994), notes a causal relationship following the eruption of Puyehue-Cordon Caulle two days after a M9.5 earthquake (1960). Based on these findings, Barrientos (1994) suggested that a volcano must be in a favourable state (i.e. exsolving gases and magma present) for strain changes, induced by an earthquake, to trigger an eruption. More recent investigations within this region include Watt *et al.* (2009); De la Cruz-Reyna *et al.* (2010); Dzierma and Wehrmann (2010) and Pritchard *et al.* (2011). In particular, Dzierma and Wehrmann (2010) and Pritchard *et al.* (2011) examine the possibility of enhanced volcanic activity following the 2010 M8.8 earthquake. Despite each paper suggesting limited responses, it is the earlier work of Watt *et al.* (2009) that quantifies the spatial extent of the relationship for all earthquakes M≥8.0 up to distances of 500 km. Further regions which have been shown to exhibit possible earthquake-volcano interactions include the 1996 earthquake-eruption sequence in Kamchatka (Walter 2007), Mauna Loa (Figure 2.5) (Walter and Amelung 2006) and the Aleutian Arc (Moran *et al.* 2002; Selva *et al.* 2004).

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Figure 2.5 Earthquake-volcano interactions at Mauna Loa (SWRZ – Southwest Rift Zone, NERZ – Northeast Rift Zone). The shaded bars represent simultaneous occurrences of earthquakes and eruptions; overall a temporal pattern (2 years) can be recognised (Source: Walter and Amelung 2006: 6).

While it is apparent that these studies have examined some of the most obvious earthquake-volcano interactions, it must also be noted that a number of other volcanic features (increased volcanic seismicity and deformation) have been documented following large earthquakes (Hill *et al.* 1993; Sturtevant *et al.* 1996; Power *et al.* 2001; Husen *et al.* 2004a; Pritchard and Simons 2004; Brodsky and Prejean 2006; Davies *et al.* 2008; Agustan *et al.* 2012). Despite the rarity of these events, perhaps one of the clearest cases is the triggered seismicity at a number of volcanic and geothermal sites (up to 1250 km away) following the 1992 M7.3 Landers earthquake (Hill *et al.* 1993; Johnston *et al.* 1995; Sturtevant *et al.* 1996). Of particular relevance, the triggered seismicity at Long Valley Caldera was thoroughly researched and documented (Hill *et al.* 1995). Significantly, these areas of triggered activity were most closely associated with young volcanoes or volcanoes that have been active in the last 1 million years (Hill *et al.* 1995; Johnston *et al.* 1995).

Following these first documented examples, further studies have since noted triggered seismicity at a number of volcanic regions around the world. Yellowstone caldera, in particular, displayed increased seismicity following the M7.9 Denali fault earthquake (Husen *et al.* 2004a; Husen *et al.* 2004b). Similarly, Power *et al.* (2001) recorded a seismic response of the Katmai volcanoes following a M7.0 earthquake in Karluk Lake. Here, volcanic observations were used to examine the underlying cause of response. Once again, the paper concluded that dynamic stress changes are largely accountable for increased volcanic response; however, the failure of this paper to prove this occurrence statistically limits the credibility of the conclusions drawn. Finally, West *et al.* (2005) documented triggered seismicity at Mount Wrangell following the 2004 M9.3 earthquake (in Indonesia). The specific relevance here is that these occurrences support previous research which suggested stress changes as the most likely trigger. In this regard, it must be considered that although explosive eruptions may not be of direct consequence, the processes that occur following an earthquake may initiate volcanic unrest that will eventually culminate in an eruption.

With these relationships in mind, further studies that are applicable to this thesis involve a review of individual earthquake and volcano characteristics. Firstly, relationships between characteristics, such as earthquake magnitude, rupture length, rupture area and displacement are thought to provide precursory estimates on the location and magnitude of future events (Wells and Coppersmith 1994). What is more, it has been noted that earthquakes alter the stress around a fault and on the basis of this; future earthquakes may be enhanced or suppressed by previous events (Stein 1999; Freed 2005), a principle which may equally apply to volcanic activity following an earthquake. In terms of large scale tectonic activity, studies have also identified the value of small scale seismicity (Kafka 2002; Helmstetter 2003). Based on this, it is possible that the tectonic environment may affect the relationship between different geological hazards, a factor that will be considered and assessed during this research.

Equally, volcano characteristics enable periods of increased activity to be identified. Volcanic seismicity, in particular, provides a reliable precursor, in the majority of cases, to impending eruptions (Tokarev 1971; McNutt 1996; McNutt 2002). Coupled with increased seismic monitoring around volcanoes, long term thermal monitoring has enabled patterns of activity to be determined (Collombet *et al.* 2003). Additionally, further research has revealed that some volcanoes exhibit a degree of seasonality (Mason *et al.* 2004). With this in mind, it is apparent that the study of eruption triggering by earthquakes must first establish if a volcano has a cyclical nature before investigating any relationship.

2.2 Remote Sensing for Volcanology

The potential of satellites to produce remotely sensed imagery for volcanology has been recognised since the 1960s, however; early remote sensing missions merely highlighted their qualitative utility to identify features of volcanic surfaces and eruptions (Gawarecki *et al.* 1965; Williams and Friedman 1970; Francis and McAllister 1986). With a view to explore the quantitative utility of satellite observations, further attempts went on to detail their application at Lascar (Francis and Rothery 1987; Glaze *et al.* 1989). While Francis and Rothery (1987) used four Landsat images to calculate the radiant temperature of thermal anomalies (Figure 2.6), Glaze *et al.* (1989) used data from the Landsat TM satellite to measure the thermal budget of the volcano. However, due to the limitations of these early methods and platforms (spatial resolution, temporal coverage and failure to define extent and intensity of activity), more recent assessments have developed sensor specific methods (Kaufman *et al.* 1998; Dehn *et al.* 2000; Wright *et al.* 2002). Most notably, computer based algorithms which use a sequence of calculations and defined thresholds have been developed which can increase the processing speeds and reliability of thermal anomaly detections whilst limiting the number of false detections.

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Figure 2.6 (a) Band 5 Landsat TM image (b) Band 7 Landsat TM image showing thermal anomalies at Lascar. The thermal anomaly is approximately 150 x 150 m in diameter and is located in one of the volcanoes youngest craters (Source: Francis and Rothery 1987: 616).

At the forefront of these developments, the Advanced Very High Resolution Radiometer (AVHRR) has been recognised as an appropriate thermal anomaly sensor since the early 1980s (Wiesnet and D’Aguanno 1982). In particular, Harris *et al.* (1997) demonstrated the ability of this sensor for 7 active volcanoes around the world. Following the positive identification of thermal hotspots at each of these volcanoes, Harris *et al.* (1997) suggested that the application of this sensor and its associated techniques could be used to support or even substitute ground based observations.

Recognising the particular utility of the AVHRR sensor, Dehn *et al.* (2000) set out the Okmok algorithm to establish the long-term thermal record of volcanoes in the North Pacific. This algorithm involves processing AVHRR data for a specific region or volcano to identify temperature increases above a local threshold which are then flagged for further analysis (Dehn *et al.* 2000). Similarly, Kaneko *et al.* (2002) developed an algorithm which conducts cloud cover assessments prior to calculating the intensity of the detected anomaly. The use of a geographic mask in which any pixel below 260 K (-13.5˚C) and being identified as cloud, is excluded from further analysis, enabled this algorithm to accurately calculate and characterise the magnitude of thermal hotspots (Kaneko *et al.* 2002).

More recently, a Robust AVHRR Technique (RAT, also RST (Robust Satellite Technique)) was set out (Di Bello *et al.* 2004; Marchese *et al.* 2006; Pergola *et al.* 2008; Lacava *et al.* 2010). Designed to monitor variations in volcanic features, this method analyses multi-spectral datasets to detect changes in volcanic activity at increased sensitivities (Marchese *et al.* 2006). However, in applying this technique to examine the presence of land surface temperature anomalies prior to the 2001 Gujarat (India) earthquake, Blackett *et al.* (2011) identified significant biases due to cloud cover and data gaps in the imagery.

An additional example of the utility of AVHRR data has been demonstrated by Webley *et al.* (2009). Specifically, AVHRR Bands 4 and 5 are used to detect volcanic ash clouds in near real-time which are then marked for analysis by the Alaska Volcano Observatory. As part of this application, volcanic ash transport and dispersion models have been identified as a valuable tool in predicting ash cloud movement (Webley *et al.* 2009).

The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor, found on-board NASA's EOS (National Aeronautics and Space Administration, Earth Observing System) satellite Terra, is another example of a sensor which can detect volcanic energy as thermal anomalies (Pieri and Abrams 2005; Vaughan and Hook 2006). Most notably, application of this sensor to Chikurachki allowed thermal anomalies to be identified up to 2 months prior to the 2003 eruption (Pieri and Abrams 2005). Furthermore, comparison of these observations to alternative sensors showed that the use of thermal anomalies is invaluable to monitor activity at volcanoes (Figure 2.7).

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Figure 2.7 Comparison of ASTER, MODIS and MCIDAS imagery to pre-eruption and eruption phases at Chikurachki, Kuril Islands; (a, b) Daytime ASTER images, (c) MODIS imagery, (d) MCIDAS TIR imagery (Source: Pieri and Abrams 2005: 89).

Equally, application of ASTER data to Mount St. Helens by Vaughan and Hook (2006) enabled the thermal behaviour of the volcano to be identified. Here, changes in radiance were related to phases of dome growth at the volcano. In addition, comparison of these results to MODVOLC data (an automatic detection system, detailed in Section 2.3) identified the need to characterise local statistics and background radiance for thermal detection algorithms to be effective (Vaughan and Hook 2006).

Of particular relevance to this thesis, the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on board NASA's Terra and Aqua platforms has been recognised as a reliable tool for hotspot monitoring (Justice *et al.* 2002). The potential of this low spatial, high temporal imagery has been recognised by many and, as a result, a number of algorithms, including MOD14 and MODVOLC, have been developed (Kaufman *et al.* 1998; Flynn *et al.* 2002). The MODVOLC algorithm has shown particular utility for volcanic hotspot monitoring in near real-time (Wright and Flynn 2003; Tralli *et* *al.* 2005). For example, in applying this algorithm to the Nyiragongo volcano, Wright and Flynn (2003) successfully identified an active lava-lake and indicated the potential of this sensor for early warning and response.

In addition, alternative semi-automatic algorithms have been developed to monitor activity at volcanoes using MODIS data (Kervyn *et al.* 2006, Koeppen *et al*. 2011). For example, the MOLDEN algorithm used by Kervyn *et al.* (2006) is based on a spatial NTI (Normalised Thermal Index) threshold. In this work, Kervyn *et al.* (2006) demonstrated the applicability of this technique to detect moderate- and high- level volcanic activity at Oldoinyo Lengai volcano. Another similar extension is the hybrid approach (Koeppen *et al*. 2011). By enhancing MODVOLC and incorporating an RST algorithm, Koeppen *et al.* (2011) defined a time series approach which allows the normal thermal character of a volcano to be identified. The study concluded that this approach was capable of detecting 15% more thermal anomalies than MODVOLC and, in addition, was more sensitive to low temperature anomalies (Koeppen *et al.* 2011).

Overall, it is evident that satellite remote sensing provides a valuable means of monitoring activity at volcanoes that are poorly instrumented or volcanoes that are located in particularly remote areas. What is more, the acquisition of data in the Middle-Infrared (MIR) and Thermal-Infrared (TIR) wavebands highlights the potential for thermal anomaly monitoring in near real-time and, more importantly, aids the development of early warning systems.

2.3 MODIS Volcanic Hotspot Detections

As discussed previously, the MODIS sensor has seen a number of algorithms developed for the purpose of thermal hotspot detection. Originally developed to overcome some of the limitations of previous sensors (sensor saturation, atmospheric disturbance and sensor radiometric response), the MODIS sensor is equipped with 36 spectral bands, 10 of which have particular utility for thermal anomaly detection (Kaufman *et al.* 1998; Flynn *et al.* 2002; Koeppen *et al.* 2011). Launched as part of NASA's EOS project, many of these products were originally developed for fire mapping and research on global change (Kaufman *et al.* 1998; Justice *et al.* 2002; Morisette *et al.* 2005; Wooster 2007). However, due to the similar thermal emissions of fires and volcanoes, these algorithms can also be applied to volcanic heat anomalies (Flynn *et al.* 2002). Currently, the level 2 MODIS fire product (MOD14/MYD14, Version 5) is a widely used detection algorithm, providing a basic thermal anomaly detection product as well as providing a basis from which higher level products are developed (Justice *et al.* 2002; Wright *et al.* 2002; Cardoso *et al.* 2005).

The MOD14 algorithm functions using a combination of MIR Bands 22 (4µm, 21 if temperature exceeds 315 K) and 31 (11µm) to identify hotspots on a per-pixel basis (Justice *et al.* 2002). Here, the algorithm assesses the response of the MIR and TIR wavebands to thermally anomalous pixels in comparison to cooler surrounding pixels (Giglio *et al.* 2003; Morisette *et al.* 2005; Hawbaker *et al.* 2008). Based on this, classifications of absolute and relative fire detections are calculated using the following algorithm on night-time imagery:

$$\{T_4 > mean\ (T_4) + 3stddev\ (T_4)\ or\ T_4 > 315\ K\}$$

and

$$\{T_4 - T_{11} > median\ (T_4 - T_{11}) + 3stddev\ (T_4 - T_{11})\ or\ T_4 - T_{11} > 10\ K\}$$

or

$$T_4 > 330\ K \qquad \text{(Eq. 2.1)}$$

(Justice *et al.* 2002)

Where T_4 = MODIS Band 22(21) (4µm) and T_{11}=MODIS Band 31 (11µm).

The particular utility of this product is supplemented by the MIR radiance method which extracts and quantifies the radiative power of detected anomalies (Wooster *et al.* 2003). Based on estimations of MIR radiance and MIR background radiance (Equation 2.2), this method assumes a linearly proportional relationship between fire radiative power (W m^{-2} sr^{-1} $\mu m^{-1}1$) and radiance as detected by the MIR waveband (Wooster *et al.* 2003). By relying on the principles of Planck's Law, in which anomalies are identified based on the difference in slope between two points (Figure 2.8), this method corrects for atmospheric effects and is insensitive to cooler background temperatures (Wooster *et al.* 2003).

$$FRE_{MIR} = 1.89 \times 10^7 (L_{MIR} - L_{MIR,bg}) \qquad \text{(Eq. 2.2)}$$

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Figure 2.8 Planck's curve for thermal anomalies detected by Band 22(21) (4µm) and Band 32 (12µm), the right axis represents the calculated different between Band 22(21) and Band 32 (Source: Wright *et al.* 2002: 5).

In terms of atmospheric correction (removing the effects of the atmosphere on reflectance), atmospheric transmittance, as calculated by the MODTRAN (MODerate resolution atmospheric TRANsmission) radiative transfer code, was identified as an appropriate algorithm to calculate the emission and absorption of infrared radiation (Berk *et al.* 1989; Wooster *et al.* 2003). Developed by the Geophysics Division of the Air Force Phillips Laboratory, this model computes the scattering of radiation due to clouds and aerosols (Berk *et al.* 1998; Wang *et al.* 2002).

Alongside this and, as a result of the requirements for a detection algorithm specifically for volcanic heat anomalies, the Hawaii Institute of Geophysics and Planetology (HIGP) developed MODVOLC, an automatic detection and monitoring system (Wright *et al.* 2002). The online web application of MODVOLC presents a global thermal monitoring system which provides information on the thermal activity of volcanoes at a 1 km resolution (Figure 2.9) (Wright *et al.* 2004). Similarly to MOD14, the MODVOLC algorithm exploits the principle that hotspots within thermally homogeneous surroundings cause the amount of radiation in the MIR waveband to increase more than in the TIR waveband based on Planck's Law (Figure 2.8) (Flynn *et al.* 2002; Wright *et al.* 2002).

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Figure 2.9 Example of thermal anomalies for Nyiragongo and Nyamuragira, measured from 19 April 2006 to 16 April 2007, as detected by the MODVOLC algorithm (Source: HIGP 2012).

The MODVOLC algorithm, explained in Figure 2.10, functions by calculating a global NTI using Bands 22(21) and 32:

$$NTI = \frac{R_{22} - R_{32}}{R_{22} + R_{32}} \qquad \text{(Eq. 2.3)}$$

Where, R_{22} = spectral radiance (W m^{-2} sr^{-1} μm^{-1}) in Band 22 (4µm) and R_{32} = spectral radiance (W m^{-2} sr^{-1} μm^{-1}) in Band 32 (12µm). If Band 22 is saturated (temperatures exceed 335 K), radiance data from Band 21 is used (Wright *et al.* 2004).

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Figure 2.10 Flow diagram of the MODVOLC night-time algorithm (Source: Wright *et al.* 2004: 36).

In order to achieve optimal thermal anomaly detections whilst also limiting the number of false detections a global NTI of -0.80 must be exceeded for a pixel to be flagged as a 'hotspot' (Wright *et al.* 2002; Wright *et al.* 2004). However due to the fixed threshold defined by this NTI approach, a number of limitations have been identified. Firstly, this global threshold (NTI≥-0.80) has resulted in a lack of sensitivity to low level thermal anomalies (Wright and Flynn 2003; Wright *et al.* 2004; Vaughan and Hook 2006). In this respect, low temperature volcanic features are not detected and alerts are not triggered. The similar thermal emissions of fires and volcanoes also present a limitation as the algorithm alone cannot discriminate between different thermal features (Wright *et al.* 2004; Rothery *et al.* 2005). Further to this, the algorithm does not quantify the radiative power of a detected anomaly and, as a result, quantitative analysis using MODVOLC results are limited (Wright *et al.* 2002). The presence of clouds can also cause problems. Firstly, clouds can mask a hotspot resulting in missed detections and, in addition, the radiances presented by clouds can, in some cases, cause false detections (Rothery *et al.* 2005). Finally, although the current MODVOLC algorithm uses only night-time data (Wright *et al.* 2002), researchers have developed a day-time version and, as a result, limitations are presented due to contamination by solar radiance (Flynn *et al.* 2002).

Despite this, MODVOLC serves as a rapid hotspot detection system which has a proven utility to volcano monitoring providing both substitute data and adding to the record of global volcanic activity (Wright *et al.* 2002; Rothery *et al.* 2005). The application of MODVOLC to monitor volcanoes, especially those with poor monitoring equipment, has provided a bank of useful case studies; which include the monitoring of Shiveluch, Kamchatka (Figure 2.11) and the observation of thermal anomalies before, during and after the 2002 eruption of Nyiragongo, D. R. Congo (Wright and Flynn 2003; Wright *et al.* 2004).

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a) **b)**

Figure 2.11 Volcanic eruption at Shiveluch, Kamchatka, (a) Image map (1 May 2002) from HIGP MODVOLC website, (b) Band 22 (4μm) spectral radiances, as detected by the MODVOLC algorithm, 1 May 2002 indicated by red circle (From: Wright *et al.* 2004: 43; 45).

Recognising the utility of the MODVOLC algorithm, further research has been directed to refine the technique. Wright and Flynn (2004), for example, use data collected by the algorithm to calculate the radiative power of volcanoes. This work outlines a method to calculate the radiative power of a pixel, as defined by Kaufman *et al.* (1998). Here, radiances as detected by Bands 22(21) and 32 are converted to temperature using Planck's blackbody radiation law (Wright and Flynn 2004). These resulting temperatures are then used to calculate the radiative power (MW) which gives an indication of the intensity of activity at a volcano (Equation 2.4) (Wright and Flynn 2004).

$$E_f = 4.34 \times 10^{-19}(T_{4h}^8 - T_{4b}^8) \qquad \text{(Eq. 2.4)}$$

Where E_f = Radiative Power, T_{4h}^8 = Band 22(21) and T_{4b}^8 = Band 32.

Overall, MODIS and its associated algorithms allow a non-interactive monitoring approach in which thermal hotspot identification can create advantages for hazard assessment and mitigation. Furthermore, the utility of MOD14 and MODVOLC enables the spectral and spatial characteristics of an anomaly to be determined, properties of which will be used during the analysis phase of this research.

2.4 The Use of MODIS and the MODVOLC Algorithm to Monitor Volcanoes

Emerging from the development of MODIS and the MODVOLC algorithm, a number of studies have been conducted to assess the activity of volcanoes and the utility of MODVOLC. In particular, Wright and Flynn (2004) use data from MODVOLC to calculate the contribution of thermal energy from active volcanoes to the earth’s energy budget. Here, the radiative power was calculated (Equation 2.4) for 45 active volcanoes, 2001-2002 (Wright and Flynn 2004). Overall, the results show a steady state of output which is influenced by large eruptions (Figure 2.12), however, Wright and Flynn (2004) accept that the insensitivities of MODVOLC (described in Section 2.3) mean that the calculated energy budget is not correct.

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Figure 2.12 Total radiative power of 45 active volcanoes, 2001-2002. A steady state of power output can be seen with increases (spikes) during large eruptions (From: Wright and Flynn 2004: 189).

Following this, Wright *et al.* (2005) used a suite of satellite datasets, including MODVOLC, to document a chronology of activity during the 2003 eruption of Anatahan. By combining the results from the MODVOLC algorithm with ground based observations, this research successfully identified the location and sequence of the eruption, Figure 2.13 (Wright *et al.* 2005). Based on this, Wright *et al.* (2005) concluded that satellite datasets, in particular MODVOLC, can be used to monitor the activity of volcanoes that are located in remote areas or have poor monitoring equipment.

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Figure 2.13 Data from the 2003 eruption of Anatahan, Mariana Islands; (a) location of thermal hotspots in the eastern crater as detected by MODIS (11^{th} May – 29^{th} May 2003), (b) sequence of eruption calculated as radiative power (MW) (11^{th} May – 29^{th} May 2003) (Source: Wright *et al.* 2005: 108).

A further example which extends the work of Wright and Flynn (2004) is Wright and Pilger (2008). In this work, they calculate the radiative power of 65 active volcanoes, 2000-2006. Similarly to Wright and Flynn (2004), Wright and Pilger (2008) found a steady release of energy during the study period, adding that variations in power could be used as indicators to changes in eruption intensity. Alongside this, Vaughan *et al.* (2008) suggested the use of thermal anomalies to forecast future eruptions. By using the extended MODVOLC approach, MOLDEN, Vaughan *et al.* (2008) identified the usefulness of MODIS data for time series analysis of thermal activity and the complementary nature of ASTER data to provide detailed information on eruption sequence. In addition, Vaughan *et al.* (2008) noted a possible causal relationship between earthquakes and volcanoes following a change in eruption style after two large earthquakes.

Finally, Coppola *et al.* (2012) identified the use of MODIS data to provide information on eruption onset at Stromboli. Using similar principles to the MODVOLC algorithm, Coppola *et al.* (2012) used Band 22(21) data and background radiances to calculate the radiative power of the volcano, 2000-2011. Overall this study successfully identified two regimes of thermal activity at Stromboli, aiding monitoring and forecasting.

2.5 The Use of Remote Sensing and Related Algorithms to Monitor the Relationship between Earthquakes and Volcanic Activity

Alongside these studies, researchers have begun to apply these techniques to study the possible relationship between seismic activity and volcanic eruptions. Moran *et al.* (2002) first introduced this application of remote sensing in an attempt to explore the influence of a M5.2 earthquake on the eruption of Shishaldin. Although based on qualitative observations, this early work used satellite and seismic records to investigate any relationship (Moran *et al.* 2002). Mirroring previous work which used ground-based observations (Brodsky *et al.* 1998; Linde and Sacks 1998), Moran *et al.* (2002) suggested a two-way coupling, further indicating that tectonic earthquakes could be used as a precursory indicator to volcanic eruptions.

Concentrating on the response of two volcanoes, Merapi and Semeru, to a M6.4 earthquake, Harris and Ripepe (2007) used MODVOLC data to calculate changes in radiative power over a 35-day window. Enhanced thermal output was recorded for up to 9 days following the earthquake and was further divided into three phases of activity (Harris and Ripepe 2007). Based on this, responses were suggested to be due to changes in stress which occur below the earth’s surface thus providing insights into the processes which may cause the relationship (Harris and Ripepe 2007).

In an effort to assess the impact of the recent M8.8 earthquake in Chile (2010), Pritchard *et al.* (2011) used MODIS, ASTER and InSAR (Interferometric Synthetic Aperture Radar) data to detect changes in volcanic activity. Interestingly, and in contrast to previous earthquake-volcano interactions in the area, the 2010 event does not appear to affect volcanic activity. In addition, Pritchard *et al.* (2011) suggests that comparisons of other large earthquakes that have occurred since 2000 could provide information on the relationship between earthquakes and volcanoes.

Of particular relevance to this thesis, Delle Donne *et al.* (2010) used MODVOLC data to study the response of volcanoes to earthquakes at a regional (750 km) and global scale. Concentrating on active volcanoes, MODVOLC data was used to calculate the radiative power (Equation 2.4) of 65 active volcanoes, 2000-2006 (Delle Donne *et al.* 2010). These calculated values were compared to all M≥4.5 earthquakes to assess the response of volcanoes over a 30-day window (Delle Donne *et al.* 2010). The results from this study indicated that at a global scale, 4 out of 7 earthquakes were followed by increases in volcanic activity and, at a regional scale, 37% of active volcanoes had increases in radiative power following an earthquake (Delle Donne *et al.* 2010). Based on these results a three stage response was suggested in which activity was noted for up to 50 days after the earthquake (Delle Donne *et al.* 2010). Corresponding with previous studies, Delle Donne *et al.* (2010) suggested that earthquake-volcano interactions were due to changes in stress, further surmising that a number of other factors also influence the significance of the relationship. In light of this, Delle Donne *et al.* (2010) conducted further analyses which incorporated factors such as earthquake orientation and response proportion (Figure 2.14), concluding that a volcano must be in a critical state for a response to occur.

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Figure 2.14 Correlation of factors that contribute to a relationship between earthquakes and volcanoes; (a) response proportion and earthquake magnitude, (b) distance and earthquake magnitude, (c) duration and earthquake magnitude, (d) volcano azimuth and earthquake fault strike (Source: Delle Donne *et al.* 2010: 772).

Overall this application of remote sensing has begun to fill a noticeable gap in the study of earthquake-volcano interactions. Despite their successes, the constraints of both this new technology and the studies themselves, limits each researcher's ability to produce robust and unbiased results. Firstly, the use of the MODVOLC algorithm provides a useful avenue in which to assess volcano response, however, the associated limitations of MODVOLC (described in Section 2.3) means that each study is (1) reliant of the exact location of each volcano to identify the origin of the detected hotspot and, (2) insensitive to small scale volcanic features such as degassing or strombolian activity. Furthermore, volcano-specific investigations, such as that by Harris and Ripepe (2007), limits the applicability of the results at a global scale while investigations of only active volcanoes (Delle Donne *et al.* 2010) limits the ability to (dis)prove any statistically significant relationship.

2.6 Modelling and Forecasting Volcanic Eruptions

Given the inherent threat posed by volcanic hazards, the determination of factors that initiate volcanic activity and unrest are of primary importance to aid forecasting and mitigation (Harris and Ripepe 2007). Specifically, the proposed relationship between earthquakes and volcanic activity has the potential to provide valuable insights into the processes and mechanisms that may trigger activity. As such, a review of forecast models, both conceptual and physical, outlines the contribution that this research could have on emergency planning and, in addition, identifies factors that would need to be considered when analysing any relationship.

Early work by Decker (1986) identified that statistical analyses could help establish patterns of activity. Based on observations of 5 active volcanoes, this work suggested that volcano-seismic precursors were an appropriate indicator of an impending eruption, further adding that there is a need to identify uncertainties in order for forecasting approaches to be effective.

Works by Sparks are some of the most noted volcano forecasting studies. Most importantly, these works highlighted the potential of seismic and remotely sensed datasets for volcano forecasting (Sparks 2003; Sparks and Aspinall 2004). In addition, Sparks and Aspinall (2004) and Huppert and Sparks (2006) suggested that the identification of patterns and clusters of activity can aid forecasting both spatially and temporally. Based on this, it is apparent that reliable forecasting depends on the ability to distinguish between volcanic unrest and impending eruptions.

Most notably, local seismicity has been identified as a precursory indicator of volcanic activity. In Hawaii, for example, Chastin and Main (2003) use seismic records to develop short-term forecasts for Kilauea. Additionally, Brenguier *et al.* (2008) used seismic records to forecast eruptions at Piton de la Fournaise. Based on results which showed decreases in seismic noise up to 20 days before an eruption, Brenguier *et al.* (2008) showed that for accurate forecasting, it is important to understand inter-eruption processes as well as periods of unrest. Finally, van Manen *et al.* (not published) used AVHRR data and the thermal character of Bezymianny to design an algorithm which provides alerts to impending activity at three levels. In evaluating the performance of this algorithm, it was noted that volcano specific precursors are invaluable when assessing the likelihood of an impending eruption.

In addition, earthquake forecasting studies provide an insight into possible volcano forecasting techniques. Firstly, Zhuang (2000) identified the utility of statistical modelling for earthquake forecasting. Using similar principles as volcano forecasting, Zhuang (2000) identified the ability of spatial-temporal analyses to identify patterns of activity, a principle which could equally be applied to volcano forecasting. Further to this, Szakács (2011) identified that earthquakes, like volcanoes, have a number of precursory signals, as a result, the identification of these factors is key for reliable forecasting.

Considering these factors, it is clear that the study of earthquake-volcano interactions by remote sensing would need to establish patterns of response to enable the design and implementation of a statistical forecast model. Furthermore, in addition to the factors that cause the relationship, there is a need to identify uncertainties within a volcanic system in order to effectively predict the response of volcanoes to earthquakes.

2.7 Summary

Overall, there appears to be a general consensus within the literature that there is an underlying relationship between earthquakes and volcanic activity. In addition, this chapter has introduced concepts that surround the modelling of volcanic hazards and identified the contribution that this work could have on the forecasting of volcanic activity. In a further step, the limitations of previous papers have been identified and, as such, it is clear that there is a need to standardise the approach taken so that the relationship between earthquakes and volcanoes can be identified. As a result, this research will re-address the study of earthquake-volcano interactions and develop an extended method based on the shortcomings of previous research. Specifically, this research will re-examine the approach outlined by Delle Donne *et al.* (2010) with a view to conduct further analysis using

MODIS data and provide further insight into the interactions between regional earthquakes and volcanic activity.

Chapter 3

Methods

Following a review of current literature (Chapter 2), it was shown that thermal anomaly detection systems provide a valuable means of measuring the response of volcanoes following an earthquake. This chapter outlines the methods applied in this thesis to investigate any relationship between regional earthquakes and volcanic activity. Firstly, data sources and dataset properties will be discussed, followed by the identification of the overall method. Based on this, each method will be discussed individually and recommendations from the pilot study made and incorporated into an extended method.

3.1 Volcanic and Seismic Datasets

3.1.1 MODVOLC

MODVOLC data (Bands 22(21) and 32) were obtained from the Hawaii Institute of Geophysics and Planetology (HIGP 2012). Developed as a point operation to detect and map volcanic thermal hotspots in near real-time, MODVOLC is a non-interactive algorithm that scans Level 1B MODIS data on a pixel by pixel basis (Wright *et al.* 2002; Wright *et al.* 2004). The MODVOLC algorithm (Section 2.3) uses low spatial resolution MIR and TIR data to identify sub-pixel hotspots which are then recorded as ASCII text files and disseminated on the internet (Wright *et al.* 2002; Wright *et al.* 2004). This algorithm provides data on thermal hotspots back to February 2000; however, due to design constraints of the algorithm to detect thermal anomalies with minimal false alarms, it does not detect low intensity hotspots and, as such, MODVOLC data was used for qualitative analysis in this thesis (Wright *et al.* 2002; Delle Donne *et al.* 2010).

3.1.2 MODIS

Data from the Level 2 MODIS Fire Product were obtained from NASA's Earth Observing System Data and Information System (EOSDIS) in the format: *MODIS/Terra Thermal Anomalies/Fire 5-Min L2 Swath 1km V005*. Originally designed for fire detection, the MODIS fire product is based on an algorithm first set out by Kaufman *et al.* (1998) and uses MIR and TIR channels to detect thermal anomalies on a per-pixel basis (Justice *et al.* 2002; Wright *et al.* 2004). Due to the somewhat different algorithms used for detection by MODVOLC and MOD14 (Giglio *et al.* 2003; Wright *et al.* 2004), MOD14 data was used due to its capabilities of detecting low intensity anomalies (Thorsteinsson *et al.* 2011). Furthermore, for this research only night-time data from Bands 22(21) and 31 were examined in order to limit the effects of solar contamination present in the day-time imagery (Flynn *et al.* 2002).

3.1.3 USGS Seismic Catalogue

Global seismic activity data was obtained from the USGS NEIC database (USGS 2012b). Each dataset can be obtained in spreadsheet format where the magnitude (Moment Magnitude, based on a logarithmic scale), location, time and depth (km) of the earthquake are recorded.

3.1.4 Dataset Properties

For this research, MODVOLC data was used in both stages of the method to identify all volcanoes that show a possible response to earthquakes. In particular, in the pilot study MODVOLC data was acquired for all volcanoes where activity was detected by Delle Donne *et al.* (2010) (2000-2006) and in the extended method, MODVOLC data was acquired for all volcanoes that were located within 1000 km of an earthquake epicentre (M≥8.0). Following the determination of active volcanoes, corresponding MOD14 imagery was obtained for 12 volcanoes which showed responses to earthquakes. Finally, seismic datasets were used throughout this research to search for changes in radiative power directly following an earthquake. Specifically, in the pilot study all earthquakes of M≥4.5 were examined and, in the extended method a range of earthquake magnitudes (M≥6.0) were examined.

3.2 Methods

Methods of analysing change in radiative power following an earthquake were set out in Section 2.5. Of particular relevance, Delle Donne *et al.* (2010) set out an approach which used MODVOLC and seismic datasets to investigate the relationship at a regional and global scale. As a result of the documented successes of this research, the first stage of this thesis re-examines this study, re-produces the results and identifies any shortcomings (Pilot Study). Based on this, an extended method (Section 3.4) was developed incorporating recommendations from the pilot study and was conducted using data from the MODIS fire product (MOD14) and over a longer time series (11 years as compared to 6 years).

3.3 Pilot Study

3.3.1 Method

In order to test whether active volcanoes are influenced by earthquakes, Delle Donne *et al.* (2010) correlated MODVOLC detected thermal anomalies with the NEIC global earthquake database. Firstly, thermal radiance data was acquired for 65 active volcanoes where the MODVOLC algorithm detected heat anomalies, 2000-2006. This data was then converted to radiative power, following the method of Wright and Flynn (2004) (Equation 2.4), and compared with all M≥4.5 earthquakes to search for increases in power following an earthquake. At this point, two spatial scales were identified, a regional study which included all volcanoes within 750 km of the earthquake epicentre and a global study which involved cross-checking global seismic energy releases with increases in global heat flux (i.e. the summed radiative power for all active volcanoes). Considering the results of Harris and Ripepe (2007), Delle Donne *et al.* (2010) defined a response over a 30-day window. Here, the mean radiative power of a volcano had to be at least twice as high in the 15 days following the earthquake compared to the 15 days before to be classed as responding. These positive interactions were then documented and further analysis was conducted which correlated variables such as response proportion, earthquake magnitude, fault strike and response duration to see if there were more distinct relationships at a regional scale. At the global scale, the cumulative seismic energy release and heat flux were compared to assess whether changes in radiative power corresponded with seismic events. In addition, Delle Donne *et al.* (2010) produced a set of false datasets in order to assess whether the same results could be produced by chance.

As a result of the advantages of this methodology to provide information on a volcanoes activity based on thermal anomalies, this stage of research re-examined the regional study set out by Delle Donne *et al.* (2010). In a further step, this stage of the thesis considered the methodology in comparison to previous studies (Linde and Sacks 1998; Marzocchi *et al.* 2004; Harris and Ripepe 2007) and made a set of recommendations which were incorporated into an extended method (Section 3.4).

3.3.2 Pilot Study Evaluation

Following the re-examination of the regional study, it was observed that Delle Donne *et al.* (2010) set out certain criteria which had to be met for a volcano to be classed as responding. Despite the identification of 37 earthquake-volcano interactions, comparisons to previous research within the field identified a number of potential improvements. Firstly, the 30-day response window may not represent an appropriate response period. Most notably, it was observed that for some interactions, volcanic activity within the same month of an earthquake was not considered. An example of this was identified at Barren Island where activity was detected 16 days before the earthquake, however due to the 15-day window, this activity was not considered. As a result, the calculated increase in mean radiative power identified the volcano as responding. In addition, responses of up to 50 days were recorded. Considering this, it can be suggested that this small response window does not accurately reflect ‘normal’ volcanic behaviour. The number of data points as detected by the MODVOLC algorithm also presented issues. In some cases, volcanoes classed as responding had less than five thermal anomalies. Whilst the majority of these detections may be of volcanic origin, it is possible that detected thermal anomalies located on the lower flanks of a volcano are wild fires. Finally, it was observed that a number of volcanoes had more than one earthquake-volcano interaction. Based on these findings, it may be appropriate to consider the significance of multiple volcanic responses.

3.3.3 Recommendations for Extended Method

In an attempt to determine the significance of the relationship between earthquakes and volcanoes, the following set of recommendations have been made for future investigations:

- The use of a longer response window to allow for the normal activity of a volcano to be reflected.
- The calculation of radiative power based on percentages, as set out by Harris and Ripepe (2007), to enable changes in activity to be identified.
- A minimum number of data points in order to positively identify an eruption and limit the use of wild fire detections.
- Investigations of volcanoes that show multiple responses to allow case-specific earthquake-volcano interactions to be examined.

3.4 Extended Method

Considering these recommendations, this stage of the thesis sets out an extended method which incorporates improvements based on findings from previous studies and the pilot study. As such, this stage of research had been divided into two phases to enable detailed statistical and spatial analyses to be conducted. Phase A provides a visual representation, using MODVOLC data, of all volcanoes that show a possible response to seismic events and Phase B extracts and analyses MOD14 data to help determine whether there is a statistically significant relationship between regional earthquakes and volcanic activity.

3.4.1 Phase A: Analysis of MODVOLC and Seismic Datasets

In order to establish if there are any responses to earthquakes, preliminary analysis examined the thermal response of volcanoes to large seismic events (M≥8.0). Firstly, all earthquakes (M≥8.0) that have occurred since 2000 were identified using the NEIC seismic database. For each earthquake, all volcanoes within 1000 km of the earthquake epicentre were identified and corresponding MODVOLC data was acquired. Whilst Delle Donne *et al.* (2010) uses a buffer of 750 km, a buffer of 1000 km was defined for this research based on the findings of Marzocchi *et al.* (2004) (Figure 2.1, pg. 14). For each hotspot located within close proximity to a volcano's geographic location, as defined by the Smithsonian Global Volcanism Program (2012), thermal radiance data as detected by MODVOLC was downloaded and recorded for the entire study period. Using this data, Band 22(21) and 32 radiance was converted to radiative power (MW) following the method set out by Wright and Flynn (2004) (Section 2.3). The results were then plotted on a graph and compared to all M≥7.0 earthquakes. This was done in order to assess whether smaller magnitude events were also capable of influencing volcanic activity, a principle which was discussed by Linde and Sacks (1998) and Brodsky *et al.* (1998) (Section 2.1). Finally, data for each volcano was inspected visually to assess whether changes in radiative power could be related to seismic activity and identify volcanoes for further analysis.

3.4.2 Phase B: Spatial and Statistical Analysis

Due to the complex nature of the potential relationship between earthquakes and volcanoes, more detailed analysis is warranted in order to determine whether the variables under study in this thesis (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance) explain the relationship between earthquakes and volcanic activity. Based on this, this thesis conducted further analysis on 12 volcanoes that were classed as 'responding' based on results from Phase A (Figure 3.1). Here, it can be noted that rather than examining all earthquake occurrences since 2000, volcanoes that showed multiple responses were considered. Furthermore, in an attempt to produce more robust results, this stage of research used MOD14 data and a longer time series (11 years as compared to 7 years).

Figure 3.1 Location of volcanoes identified for further analysis in this thesis (Source: ESRI 2009).

Following the identification of 'responding' volcanoes, imagery from the MODIS Fire Product (MOD14) was acquired. Using the MIR radiance method (discussed in Section 2.3); the radiative power of detected thermal anomalies was extracted from the product following the revised method of Wooster *et al.* (2003), amended for atmospheric transmissivity and pixel size variation (Wooster *et al.* 2005):

$$\mathrm{FRP}_{MIR} = A \times 20.25 \times \left(L_{MIR} - L_{MIR,bg}\right)\left(\frac{1}{\tau_\lambda}\right) \qquad \text{(Eq. 3.1)}$$

Where A = pixel area dependant on scan angle (m^2), L_{MIR} = MIR spectral radiance of the thermally anomalous pixel (W m^{-2} sr^{-1} μm^{-1}), $L_{MIR,bg}$ = MIR spectral reflectance of surrounding background pixels (W m^{-2} sr^{-1} μm^{-1}) and τ_λ = atmospheric transmittance. Atmospheric transmittance values were derived from Blackett (2009), where the MODTRAN algorithm was used to calculate the amount of atmospheric radiative transfer between the sensor platform and volcanic surface.

Each flagged anomaly was then recorded (days in which multiple detections occurred were summed to give the total radiative power for that particular day) and compared to MODVOLC data to ensure that the datasets was comparable (Figure 3.2). At this point, however, it was observed that at certain volcanoes the MOD14 fire product detects (and quantifies) significantly fewer thermal anomalies than the MODVOLC application, a finding corroborated by Blackett (2009) and Thorsteinsson *et al.* (2011). In some respects, this may be due to the different algorithms used by MOD14 and MODVOLC (Section 2.3), however, it has been postulated that the basis of the MOD14 product may also be a contributing factor (Blackett 2009). Firstly, MOD14 functions by comparing an anomaly to surrounding pixels and in the occurrence that these pixels are either cloud or water; they are excluded from further analysis (Justice *et al.* 2002; Giglio 2010). Similarly, the background signal may cause an anomalous pixel to be undetected. Here, factors such as varying topography or volcanoes within thermally heterogeneous surfaces result in high background signals, meaning that an anomaly must also have a significantly higher temperature to be detected (Blackett 2009). Despite this, due to the higher sensitivities of the MOD14 algorithm, it was determined that MOD14 data would be used to ensure the robustness of this research. As a result, there were non-detections at 4 volcanoes and, as such, only 8 volcanoes were used for further analysis (Table 3.1).

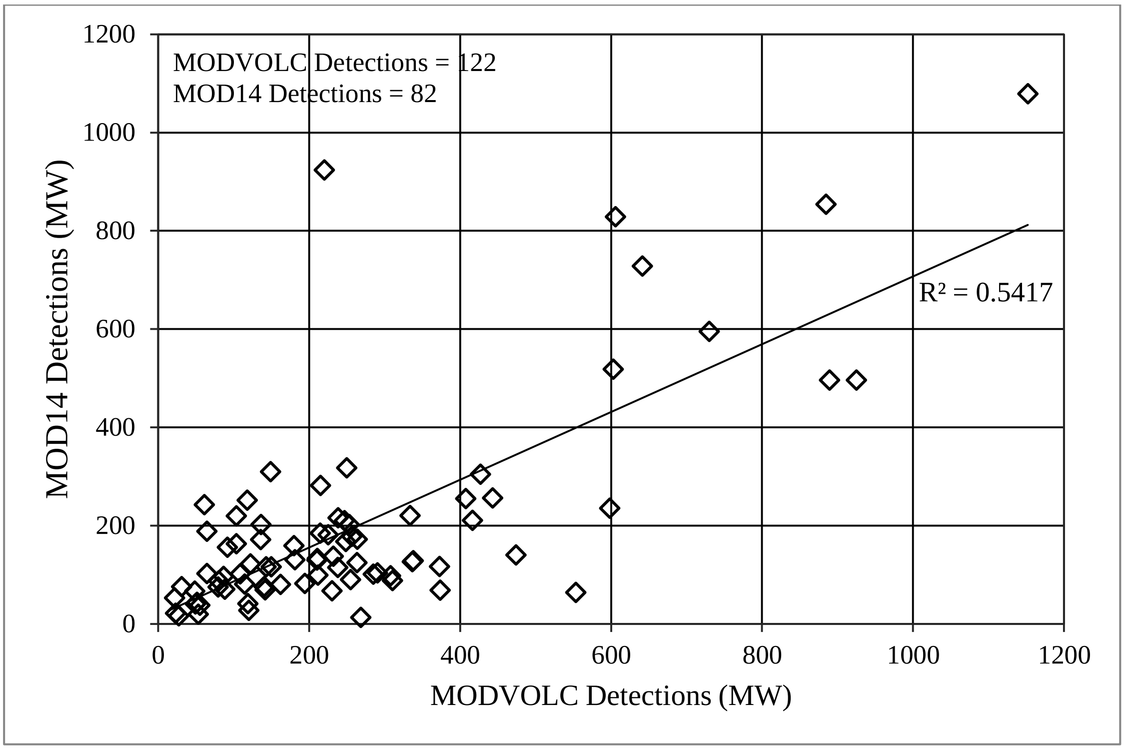

Figure 3.2 Radiative power correlations of thermal anomalies detected by the MODVOLC and MOD14 algorithms, example based on detections at Puyehue-Cordon Caulle.

Table 3.1 Volcanoes used for further analysis (Source: Smithsonian Global Volcanism program 2012).

Volcano	**Country**	**Latitude**	**Longitude**
Bagana	Papua New Guinea	-6.14	155.195
Chaiten	Chile	-42.833	-72.646
Karymsky	Russia	54.05	159.45
Langila	Papua New Guinea	-5.525	148.42
Pago	Papua New Guinea	-5.58	150.52
Puyehue-Cordon Caulle	Chile	-40.59	-72.117
Rabaul	Papua New Guinea	-4.271	152.203
Villarrica	Chile	-39.42	-71.93

Following the determination of radiative power for each volcano, all earthquakes ($M \geq 6.0$) within 1000 km of the volcano were examined for changes in power over a 180-day window (centred on the earthquake). This period was defined based on the findings of Delle Donne *et al.* (2010) who noted long response durations and to allow 'normal' volcanic activity to be reflected. Furthermore, a number of considerations based on the recommendations in Section 3.3.2 were incorporated:

- Change in summed radiative power must be at least 100% to allow responding volcanoes to be identified.
- Each interaction needs to have at least 3 thermal anomaly detections to limit the use of false detections and accurately identify erupting volcanoes.
- Responses with a number of possible influencing events will analyse the earthquake with the shortest delay based on the findings of previous research which noted small temporal delays (Linde and Sacks 1998; Delle Donne *et al.* 2010).
- For days with multiple occurrences the largest magnitude event will be considered based on the findings of Linde and Sacks (1998) who noted that large seismic events are more likely to trigger a response.
- For interactions that have earthquakes within 30 days of a response, the change in radiative power had to be at least 50% larger in order to reflect the influence on volcanic activity rather than the triggering of volcanic activity.

For each earthquake-volcano interaction corresponding variables (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance) were then recorded for further analysis based on the determination of controlling factors in previous research (Hill *et al.* 2002; Eggert and Walter 2009; Delle Donne *et al.* 2010). Statistical analyses (correlation and multiple regression) were performed to evaluate the significance of the potential relationship and spatial analyses were conducted to evaluate whether there was a spatial pattern of response. Finally, analysis of all earthquake-volcano interactions allowed typical patterns of response following earthquakes to be determined.

3.5 Summary

This chapter has presented the methods that were used to examine the thermal response of volcanoes to earthquakes. In addition, data sources and dataset properties were identified. Following the application of the methods to MOD14 and MODVOLC data, Objectives 2, 3 and 4 of this thesis have been addressed (Section 1.5). The forthcoming chapter will now present the results of these methods and analyse the findings. Particular focus is given in the pilot study to compare the results to Delle Donne *et al.* (2010) in order to exemplify the advantages of the extended method.

Chapter 4

Results

This chapter presents the results of the methodology set out in Chapter 3. Firstly, pilot study results will be presented followed by a series of maps, tables and graphs which examine the response of volcanoes to earthquakes (Extended Method). For each set of results, a synopsis of the main patterns and trends will be described.

4.1 Pilot Study Results

Of the 37 volcanoes which exhibited possible earthquake-volcano interactions, 30 (81%) were found to experience increases in radiative power following a regional earthquake (Table 4.1). All responses at a regional scale occurred within 12 days of the earthquake with the majority of responses (73%) occurring within 5 days. Figures 4.1a-4.3a show the relationship between different variable pairs as calculated in this research. Alongside these, Figures 4.1b-4.3b display the results of the correlations as produced by Delle Donne *et al.* (2010), where the white diamonds represent MODVOLC datasets.

Table 4.1 Earthquake-Volcano Interactions as detected by the MODVOLC algorithm, rows highlighted in blue indicate regional responses (750 km).

Date	Magnitude	Fault Strike (˚)	Volcano	Azimuth (˚)	Distance (km)	Temporal Delay (Days)	Response Duration (Days)
03/04/2000	6.2	-36	Karangetang	9	209	1.7	-
16/07/2000	7.3	276	Bagana	249	505	12	40
29/10/2000	7.0	322	Bagana	318	212	5	20
04/12/2000	6.1	296	Santa Maria	274	258	4	10
08/02/2002	5.4	151	Fuego	129	335	1.1	4.4
30/07/2002	6.2	161	Michael	95	193	1	24
07/10/2002	5.7	185	Yasur	169	261	1.1	6
25/09/2003	8.3	250	Karymsky	226	1778	4.5	32
25/09/2003	8.3	250	Rabaul	351	5191	13.4	-
05/12/2003	6.7	95	Klyuchevskoi	98	325	1.2	4.7
09/01/2004	6.3	90	Langila	119	137	10.5	-
14/04/2004	6.2	77	Karymsky	56	250	2.6	18.6
05/09/2004	7.5	259	Asama	201	382	9	-
03/10/2004	5.2	122	Yasur	106	56	2.8	9.1
09/10/2004	7.0	122	Fuego	126	569	2.3	-
16/11/2004	6.1	78	Langila	92	340	8	-
13/12/2004	6.0	118	Fuego	126	211	6	7
26/12/2004	9.1	129	Kilauea	100	12000	1	50
26/12/2004	9.1	129	Klyuchevskoi	70	8300	21	-
26/12/2004	9.1	129	Anatahan	81	5800	11	-
26/12/2004	9.1	129	Popocatepetl	146	17000	13.2	-
05/02/2005	7.1	338	Karangetang	321	637	0.1	-
02/03/2005	5.2	-	Fuego	-	159	1.2	4.1
14/03/2005	5.2	112	Semeru	201	134	1	3.9
28/03/2005	8.6	125	Erta Ale	96	6330	2	-
11/04/2005	6.7	267	Langila	309	359	7.7	-
11/05/2005	5.0	-	Fernandina	-	35	2.3	-
13/07/2005	5.5	4	Barren Island	26	243	1.3	9.2
09/09/2005	7.6	140	Rabaul	102	169	3	20
22/10/2005	5.5	105	Sierra Negra	98	27	0.3	-
13/11/2005	4.8	-	Lopevi	-	147	5.8	3.8
05/12/2005	7.2	193	Nyiragongo	173	518	3	20
21/12/2005	6.3	204	Soputan	183	134	6.2	-
03/03/2006	4.8	-	Augustine	-	111	2.5	8.6
12/05/2006	4.8	125	Bagana	56	91	2.9	9.6
26/05/2006	6.3	232	Merapi	180	49	3	12
26/05/2006	6.3	232	Semeru	273	272	3	12

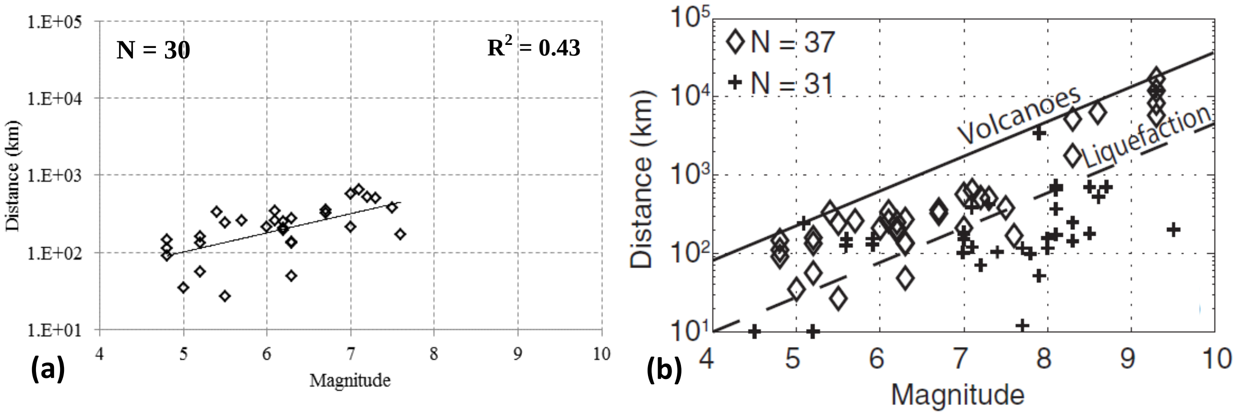

Figure 4.1 Relationship between Earthquake Magnitude and Distance to Responding Volcano; (a) calculated following the method set out in Section 3.3 and, (b) correlation as presented by Delle Donne *et al.* (2010: 772), where crosses represent results from previous studies.

As originally indicated by Delle Donne *et al.* (2010), there is a positive correlation between earthquake magnitude and distance. However, comparison of the R^2 value (0.43) to Delle Donne *et al.* (2010) (0.89) suggests the relationship is not statistically significant based on MODVOLC data alone. Furthermore, re-inspection of Figure 4.1b confirms that the R^2 value (0.89) calculated by Delle Donne *et al.* (2010) uses a number of additional datasets and, in addition, incorporates MODVOLC detections at the global scale.

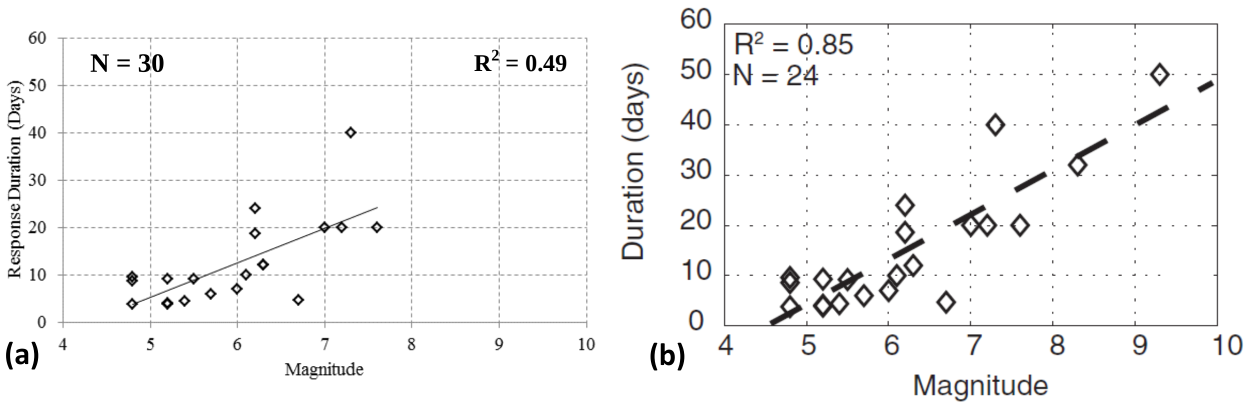

Figure 4.2 Relationship between Earthquake Magnitude and Response Duration; (a) calculated following the method set out in Section 3.3 and, (b) correlation as presented by Delle Donne *et al.* (2010: 772).

Figure 4.2 shows the relationship between earthquake magnitude and response duration. Once again, the R^2 value originally indicated by Delle Donne *et al.* (2010) (0.85) is greater than the R^2 value calculated in this research (0.49). Comparison of data points, however, reveals that Delle Donne *et al.* (2010) only uses data on the 24 volcanoes classed as responding rather than every earthquake-volcano interaction.

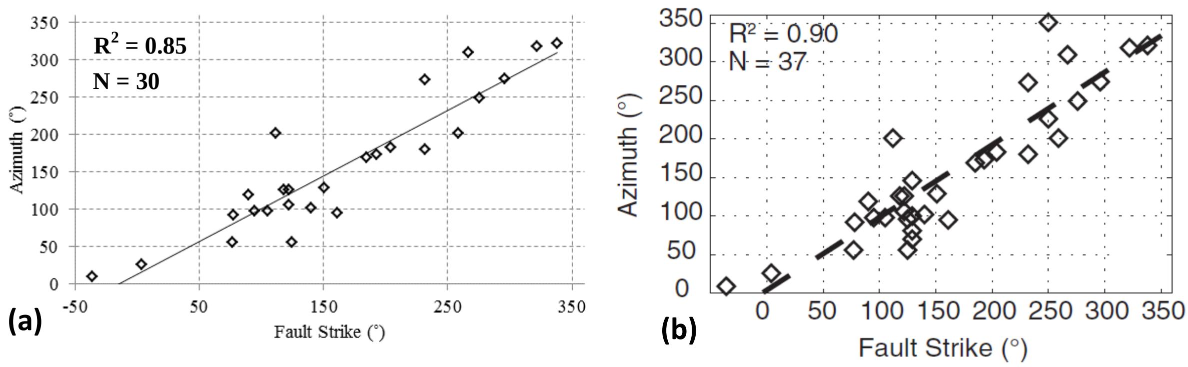

Figure 4.3 Relationship between Fault Strike and Azimuth of the Responding Volcano; (a) calculated following the method set out in Section 3.3 and, (b) correlation as presented by Delle Donne *et al.* (2010: 772).

As shown in Figure 4.3, there is a positive correlation between fault strike direction and azimuth of the responding volcano. Most notably, the R^2 values (0.85 and 0.90, respectively) are statistically significant. Comparison of results to Delle Donne *et al.* (2010), however, shows a discrepancy between data points, 30 compared to 37. Despite this, these variables appear to be a good indicator of the relationship between earthquakes and volcanic activity.

4.2 Extended Method Results

4.2.1 Phase A: Analysis of MODVOLC and Seismic Datasets Results

From the 14 earthquakes of M≥8.0 studied (Table 4.2), 51 volcanoes were found to be within 1000 km of an earthquake epicentre and were active during the study period. Of these, 24% (12) showed possible earthquake-volcano interactions (Table 4.3) with the majority (83%) occurring at volcanoes where activity was on-going when a response occurred. Figures 4.4-4.7 present the clearest patterns of response based on MODVOLC data. Most notably, each graph shows the insensitivity of MODVOLC to all anomalies below 15 MW. All large earthquakes (M≥8.0) are followed by a change in radiative power and, in addition, there are a number of individual patterns of response. The remaining volcanoes which showed possible earthquake-volcano interactions are shown in Appendix A.

- Bagana shows varying levels of response in which increases and decreases in activity are evident following an earthquake (Figure 4.4).
- The largest earthquake (M9.1) appears to be the catalyst for new activity at Barren Island, before which the volcano was relatively inactive. Following this, periods of activity particularly following an earthquake can be seen (Figure 4.5).
- Following a period of seismic and volcanic silence during 2008 and 2009, a large earthquake (M8.8) appears to initiate new activity at Villarrica. Before this event, the volcano doesn't appear to be affected by large earthquakes and, as such, it must be considered that activity at this volcano may be affected by other factors that influence volcanic unrest (Figure 4.6).
- Krakatau appears to be affected by short periods of volcanic activity with earthquakes occurring within periods of volcanic silence. Interestingly, earthquake magnitude does not appear to affect the intensity of volcanic activity (Figure 4.7).

Table 4.2 Global seismic activity data for all earthquakes M≥8.0 (Source: USGS NEIC).

Date	Time (24 Hours)	Magnitude	Latitude	Longitude	Depth (km)
23/06/2001	20:33	8.4	-16.264	-73.641	33
25/09/2003	19:50	8.3	41.815	143.91	27
23/12/2004	14:59	8.1	-49.312	161.345	10
26/12/2004	00:58	9.1	3.295	95.982	30
28/03/2005	16:09	8.6	2.085	97.108	30
03/05/2006	15:26	8.0	-20.187	-174.123	55
15/11/2006	11:14	8.3	46.592	153.266	10
13/01/2007	04:23	8.1	46.243	154.524	10
01/04/2007	20:39	8.1	-8.466	157.043	24
15/08/2007	23:40	8.0	-13.386	-76.603	39
12/09/2007	11:10	8.5	-4.438	101.367	34
29/09/2009	17:48	8.1	-15.489	-172.095	18
27/02/2010	06:34	8.8	-36.122	-72.898	22
11/03/2011	05:46	9.0	38.297	142.373	29

Table 4.3 Volcanoes that exhibit possible earthquake-volcano interactions (Source: Smithsonian Global Volcanism Program 2012).

Volcano	Country	Latitude	Longitude
Bagana	Papua New Guinea	-6.14	155.195
Barren Island	India	12.278	93.858
Chaiten	Chile	-42.833	-72.646
Karymsky	Russia	54.05	159.45
Krakatau	Indonesia	-6.102	105.423
Langila	Papua New Guinea	-5.525	148.42
Lascar	Chile	-23.37	-67.73
Pago	Papua New Guinea	-5.58	150.52
Puyehue-Cordon Caulle	Chile	-40.59	-72.117
Rabaul	Papua New Guinea	-4.271	152.203
Tinakula	Solomon Islands	-10.38	165.8
Villarrica	Chile	-39.42	-71.93

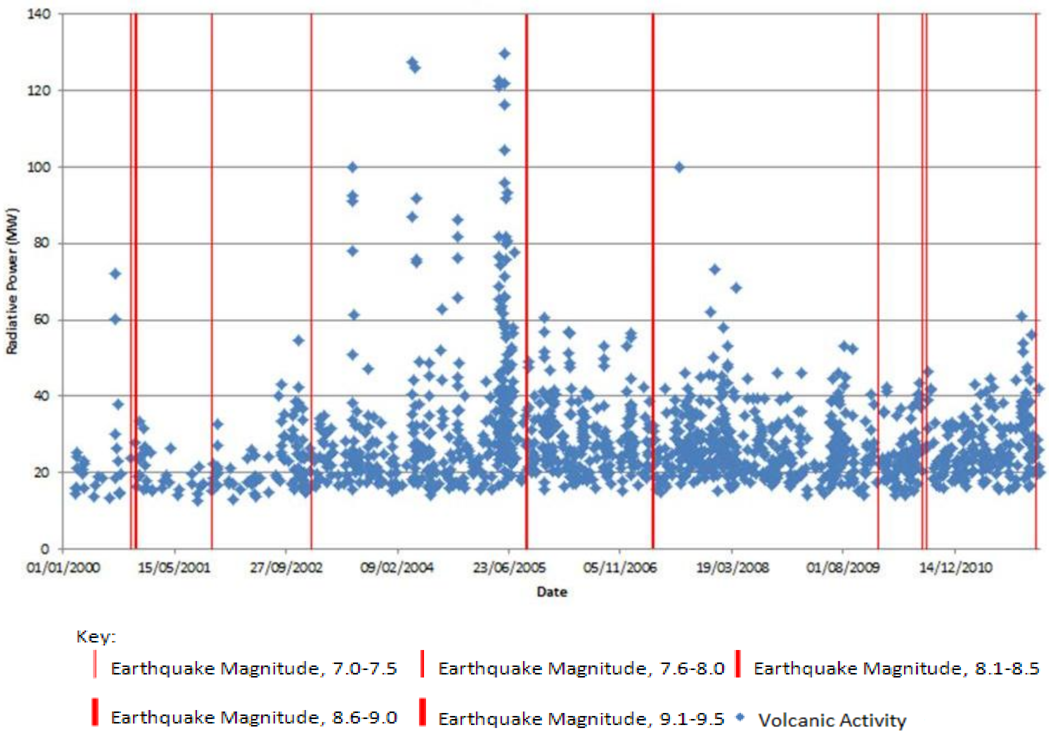

Figure 4.4 Volcanic hotspot data from Bagana (converted from thermal radiance as detected by the MODVOLC algorithm) compared to all M≥7.0 earthquakes within a 1000 km buffer zone, 2000-2011.

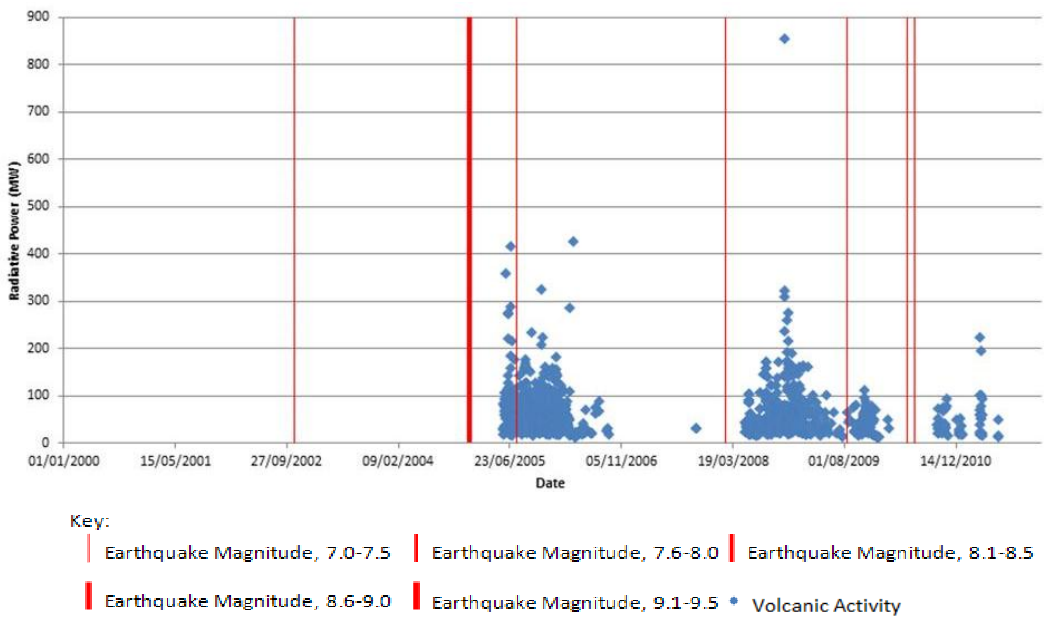

Figure 4.5 Volcanic hotspot data from Barren Island (converted from thermal radiance as detected by the MODVOLC algorithm) compared to all M≥7.0 earthquakes within a 1000 km buffer zone, 2000-2011.

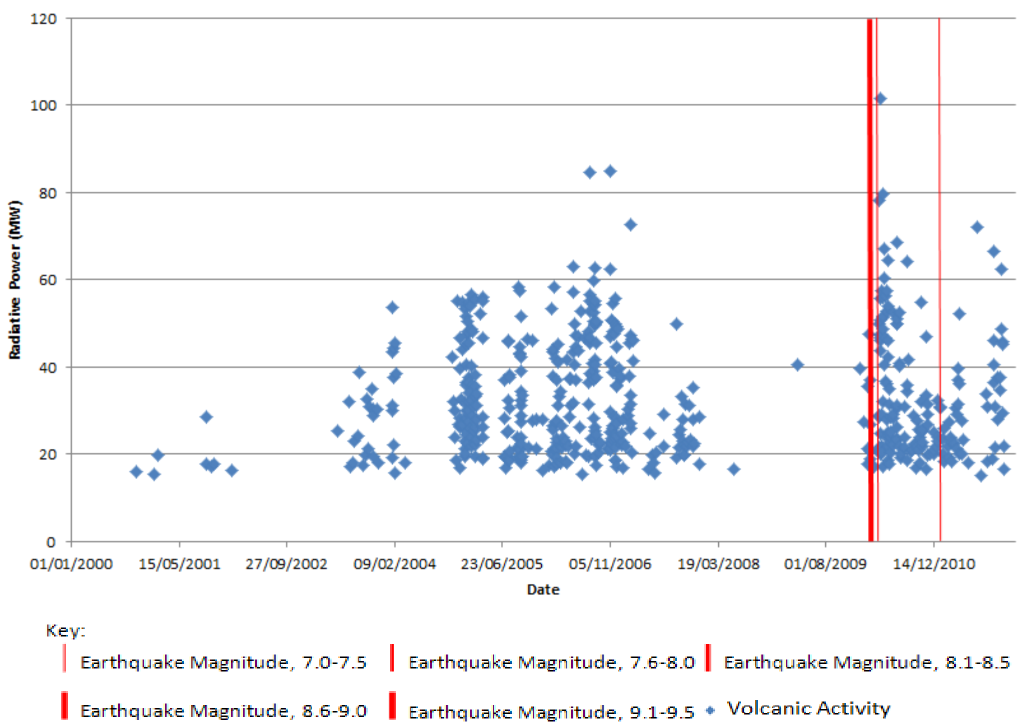

Figure 4.6 Volcanic hotspot data from Villarrica (converted from thermal radiance as detected by the MODVOLC algorithm) compared to all M≥7.0 earthquakes within a 1000 km buffer zone, 2000-2011.

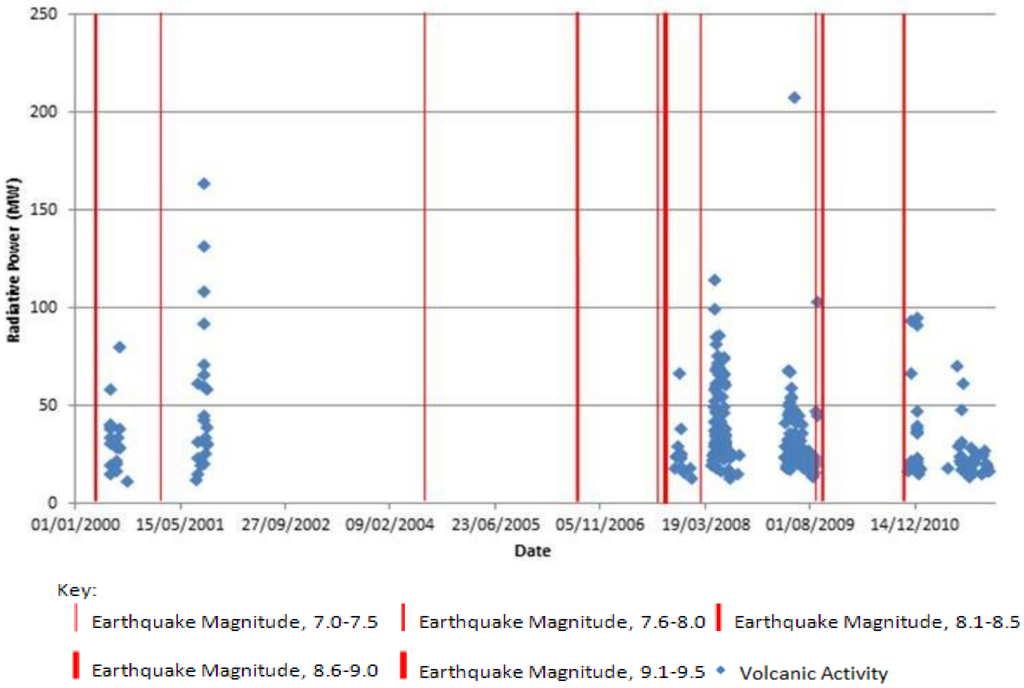

Figure 4.7 Volcanic hotspot data from Krakatau (converted from thermal radiance as detected by the MODVOLC algorithm) compared to all M≥7.0 earthquakes within a 1000 km buffer zone, 2000-2011.

4.2.2 Phase B: Spatial and Statistical Analysis Results

From the 301 earthquakes (M≥6.0) examined (Appendix B), 12% appeared to induce increases in radiative power at 7 different volcanoes (Table 4.4, Figure 4.8). Of these responses, 26 occurred at volcanoes when activity was already present and 10 were found to initiate new activity. The longest delay between earthquake occurrence and volcanic response was 50 days with the majority (83%) occurring within 30 days. Furthermore, earthquake depths in the range 30-40 km were found to trigger the most responses with the optimum distance between earthquake epicentre and responding volcano being between 300 and 400 km.

Table 4.4 Earthquake-Volcano Interactions as detected by the MOD14 algorithm.

Date	Earthquake Magnitude	Responding Volcano	Temporal Delay (Days)	Change in Radiative Power (MW)	Distance (km)	Earthquake Depth (km)	State of Volcano
06/02/2000	6.6	Bagana	26	125.84	479	33	Not Active
03/03/2000	6.6	Rabaul	44	164.24	975	10	Not Active
23/08/2001	6.2	Langila	4	111.81	338	10	Not Active
23/08/2001	6.2	Rabaul	1	131.82	663	10	Active
21/06/2002	6.0	Langila	13	581.86	221	33	Active
03/07/2002	6.2	Pago	37	2619.97	359	31	Not Active
31/10/2002	6.1	Bagana	29	82.68	786	10	Active
24/04/2003	6.1	Karymsky	31	1548.16	664	43	Not Active
07/06/2003	6.6	Rabaul	18	34.38	99	33	Active
12/06/2003	6.3	Bagana	6	349.67	51	186	Active
22/04/2004	6.0	Bagana	4	351.77	975	35	Active
16/11/2004	6.1	Langila	25	96.20	340	55	Not Active
23/02/2005	6.0	Bagana	6	119.86	502	10	Active
23/02/2005	6.0	Rabaul	6	58.06	281	10	Not Active
11/04/2005	6.6	Langila	19	1155.93	361	11	Not Active
04/06/2005	6.1	Bagana	4	311.39	924	26	Active
09/09/2005	7.6	Rabaul	28	75.98	143	90	Active
22/05/2006	6.6	Karymsky	38	319.03	838	19	Not Active
28/05/2006	6.5	Bagana	6	90.86	452	34	Active
01/04/2007	8.1	Bagana	2	191.72	328	24	Active
29/05/2007	6.1	Bagana	8	209.96	409	132	Active
01/01/2008	6.3	Rabaul	50	46.48	619	34	Active
28/07/2008	6.0	Bagana	1	55.53	999	10	Active
30/08/2008	6.4	Rabaul	9	99.73	589	75	Active
12/05/2009	6.1	Bagana	7	304.80	628	89	Active
23/06/2009	6.7	Bagana	2	130.10	191	64	Active
14/12/2009	6.0	Bagana	6	80.74	86	39	Active
01/02/2010	6.2	Bagana	12	87.63	81	32	Active
27/02/2010	8.8	Villarrica	40	265.70	375	22	Active
11/04/2010	6.9	Bagana	10	250.24	836	21	Active
17/04/2010	6.2	Rabaul	13	63.13	609	53	Active
20/08/2010	6.1	Rabaul	20	494.83	342	19	Active
02/12/2010	6.6	Bagana	6	109.92	578	33	Active
23/04/2011	6.8	Bagana	1	367.38	811	79	Active
01/06/2011	6.3	Puyehue-Cordon Caulle	5	11233.97	368	21	Not Active
14/10/2011	6.5	Rabaul	10	100.06	545	37	Active

Note: Chaiten did not record changes in radiative power of more than 100%.

Figure 4.8 Volcanoes that exhibited Earthquake-Volcano Interactions based on MOD14 data (Source: ESRI 2009).

Figures 4.9 and 4.10 display the typical patterns of response for volcanoes following an earthquake. Figure 4.9 shows that for volcanoes that were not active before the earthquake occurrence, there is a short delay between the seismic event and volcanic response. At this point, there is a rapid increase in radiative power (1500 MW) which then stabilises after the initial response. Figure 4.10 shows the typical response of erupting volcanoes to earthquakes. Following a steady increase in radiative power, it can be seen that the earthquake occurrence significantly increases the number of detections and the intensity of activity. Most notably, in the period following the earthquake there is an increase in radiative power of 100 MW which continues during the response window.

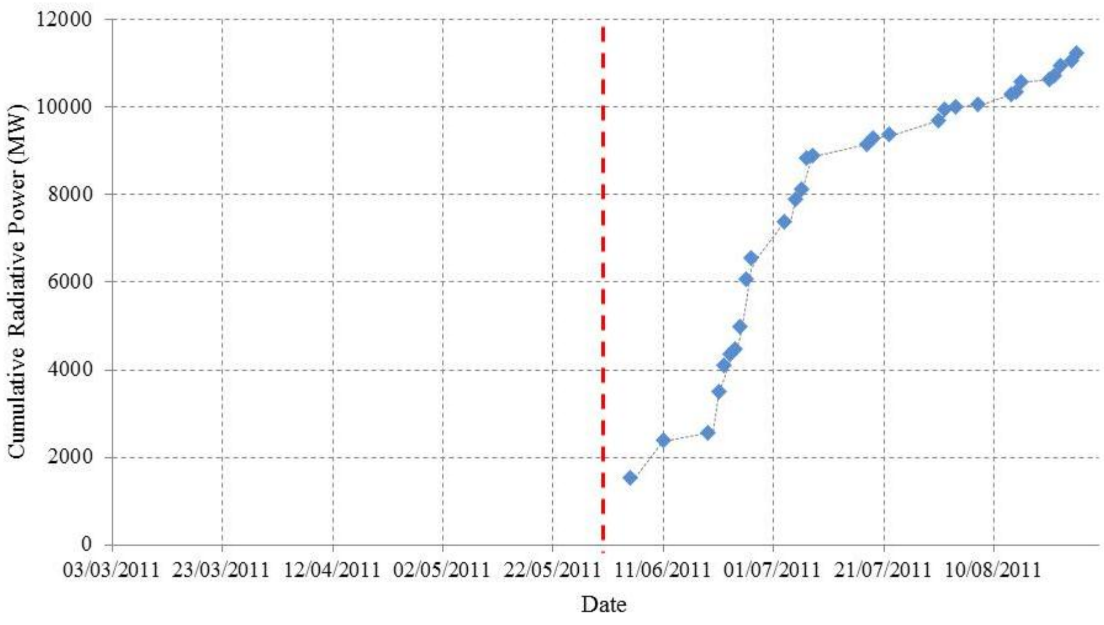

Figure 4.9 Typical pattern of response for volcanoes where activity was not present before an earthquake, example based on response of Puyehue-Cordon Caulle to a M6.3 earthquake (cumulative radiative power indicated by the blue diamonds and the earthquake is indicated by the red dashed line).

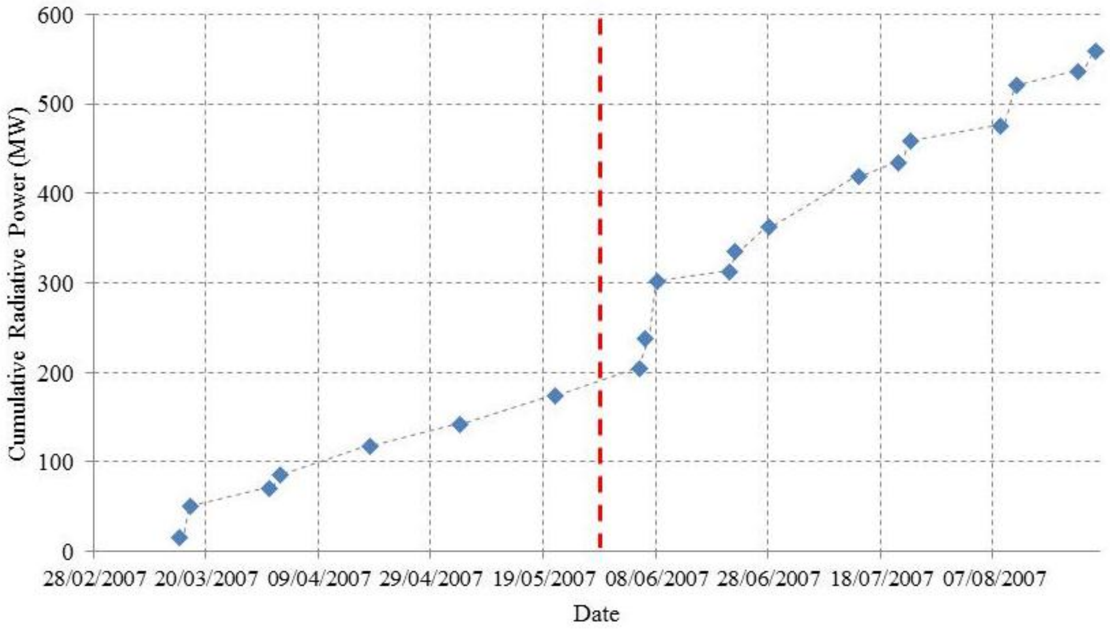

Figure 4.10 Typical pattern of response for volcanoes where activity was on-going when an earthquake occurred, example based on response of Bagana to a M6.1 earthquake (cumulative radiative power indicated by the blue diamonds and the earthquake is indicated by the red dashed line).

Table 4.5 summarises the relationship between different variable pairs (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance). Overall, there are no statistically significant relationships. Although weak, earthquake depth and distance to the responding volcano has the strongest relationship (0.09) while temporal delay and change in radiative power exhibits the weakest relationship (0.002).

Table 4.5 Relationship (R^2 value) between different earthquake-volcano variables, rows highlighted in blue are further analysed in Figures 4.11-4.13.

Variable 1	Variable 2	Regression Equation	R^2 Value
Earthquake Magnitude	Change in Radiative Power	y = -216.81x + 2023.1	0.005
Earthquake Magnitude	Temporal Delay	y = -5.4028x – 19.699	0.05
Earthquake Magnitude	Distance	y = -4.0709x + 571.01	0.02
Earthquake Depth	Change in Radiative Power	y = -4.9551x + 825.56	0.01
Earthquake Depth	Temporal Delay	y = -0.0613x + 17.701	0.03
Earthquake Depth	Distance	y = -2.2225x + 586.63	0.09
Temporal Delay	Change in Radiative Power	y = -5.6531x + 708.71	0.002
Temporal Delay	Distance	y = 1.6736x + 470.26	0.007
Distance	Change in Radiative Power	y = -0.5748x + 907.72	0.007

Note: *x = variable 1, y = variable 2*

Figures 4.11-4.13 present boxplots to illustrate the relationships highlighted in Table 4.5. Figure 4.11 demonstrates the relationship between earthquake depth and distance to responding volcano. 75% of triggering events occur at depths of less than 50 km, affecting volcanoes at distances between 200 and 800 km (Figure 4.11). Figure 4.12 shows that the majority of earthquake-volcano interactions follow small magnitude events (M≤7.0) and occur within 30 days. Finally, Figure 4.13 shows the relationship between earthquake depth and temporal delay.

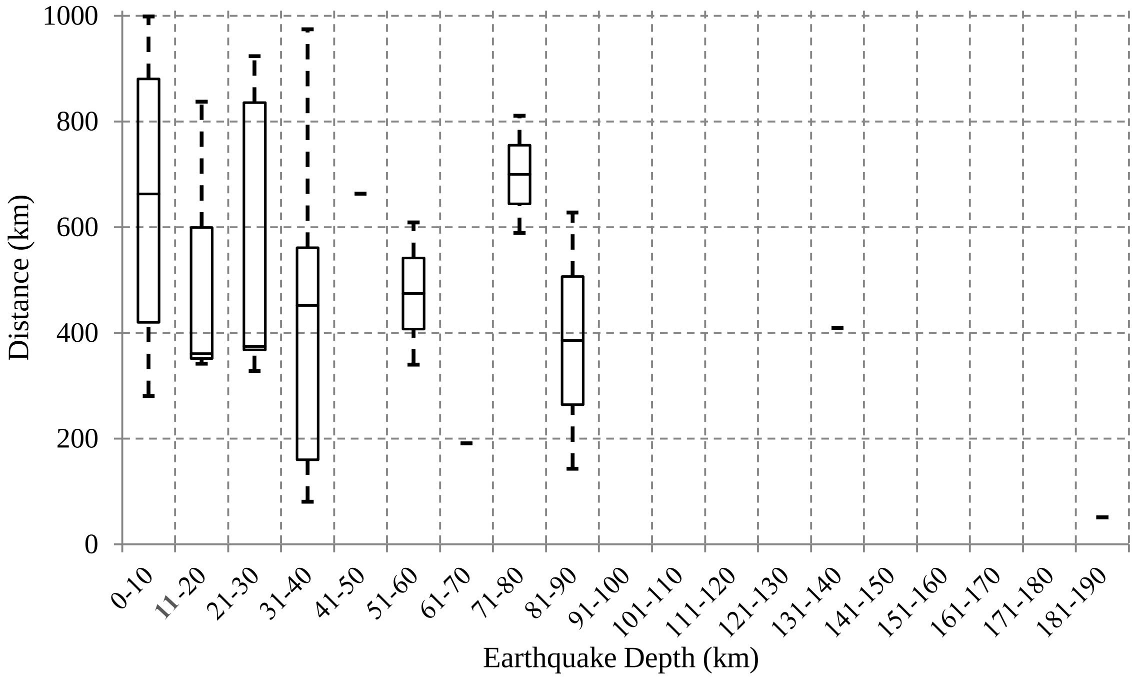

Figure 4.11 Boxplot comparing Earthquake Depth and Distance; dotted lines represent the maximum and minimum values within each range, the box represents the upper and lower quartile, within the box the horizontal line represents that median of the data.

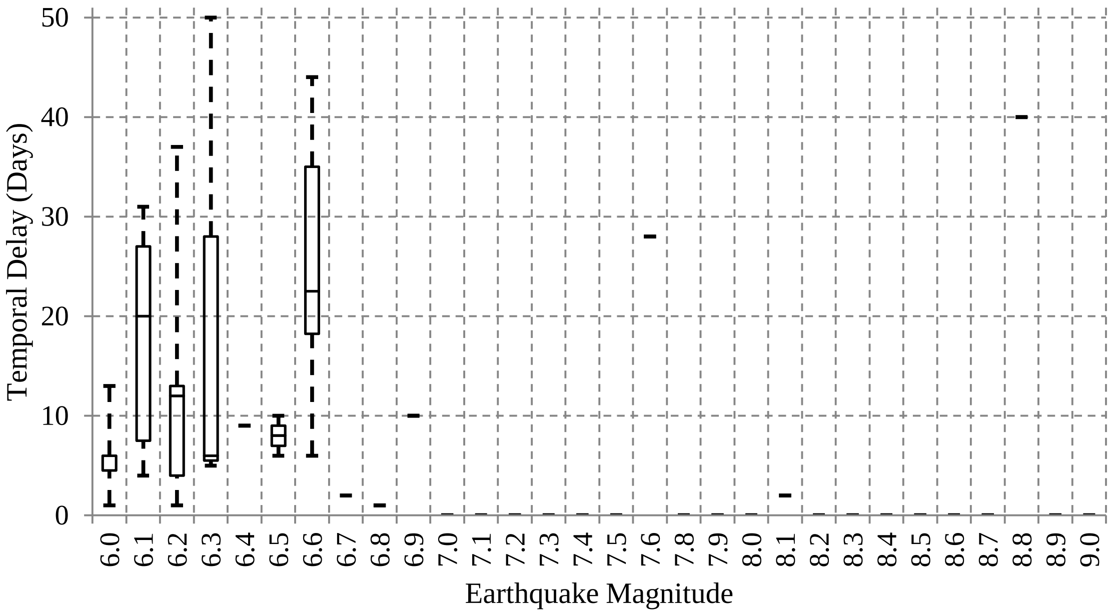

Figure 4.12 Boxplot comparing Earthquake Magnitude and Temporal Delay; dotted lines represent the maximum and minimum values within each range, the box represents the upper and lower quartile, within the box the horizontal line represents that median of the data.

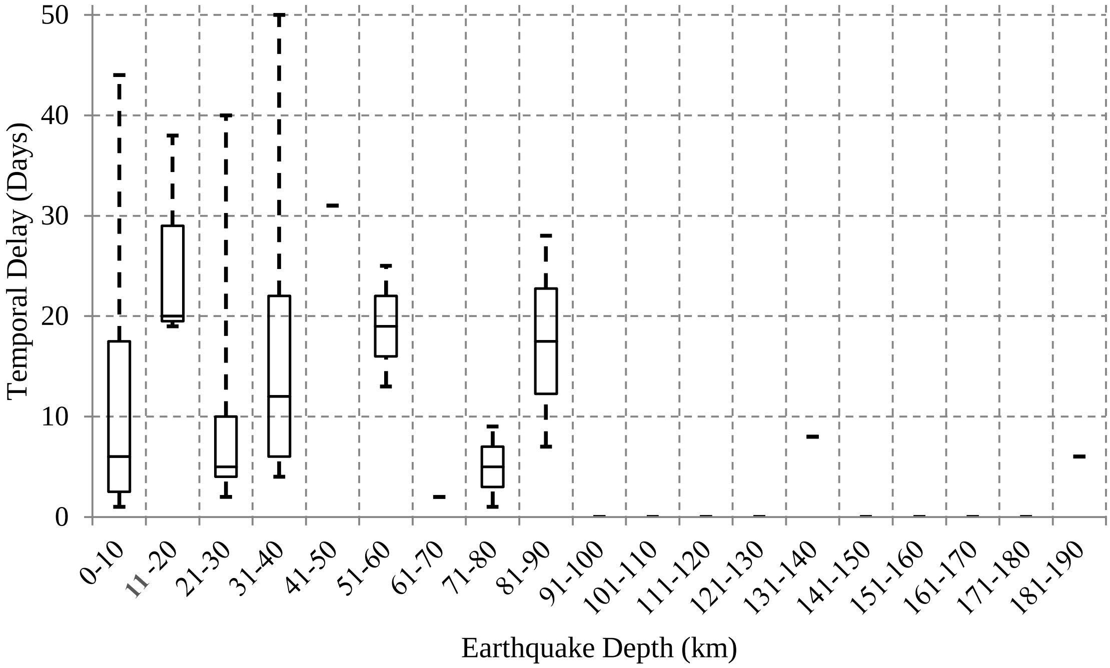

Figure 4.13 Boxplot comparing Earthquake Depth and Temporal Delay; dotted lines represent the maximum and minimum values within each range, the box represents the upper and lower quartile, within the box the horizontal line represents that median of the data.

Table 4.6 presents the results of the multiple regression analysis in which the effect of earthquake magnitude, earthquake depth, temporal delay and distance on change in radiative power are examined. Overall, it can be seen that very little variance in change in radiative power can be explained by these variables (Equation 4.1). The Adjusted R^2 value (-0.097) shows that these variables account for less than 9.7% of variance in change in radiative power. Furthermore, the *p*-value (0.920) shows that the relationships are not statistically significant and, therefore, change in radiative power cannot be explained by these variables. Finally, low beta values ($\geq$-0.150, p>0.0005) indicate that for every unit change in the predictor variable, change in radiative power does not significantly change. As a result, it can be concluded that the variables under study in this thesis do not contribute towards the response of volcanoes to earthquakes.

Table 4.6 Summary Statistics from multiple regression analysis where the dependant variable is Change in Radiative Power and the predictor variables are Earthquake Magnitude, Earthquake Depth, Temporal Delay and Distance.

An insignificant model emerged:

$$F\ (4, 31) = 0.229, p > 0.005, R^2 = 0.029 \qquad \text{(Eq. 4.1)}$$

Model Summary

R	**R^2**	**Adjusted R^2**	**Standard error of the estimate**
0.169	0.029	-0.097	1.975×10^3

ANOVA

Model	**Sum of Squares**	**df**	**Mean Square**	**F**	***p*-value**
Regression	3574476.168	4	893619.042	0.229	0.920
Residual	1.209×10^8	31	3900792.978		
Total	1.245×10^8	35			

Significance of predictor variables:

Model	**B**	**Beta**	***p*-value**
Earthquake Magnitude	-3.154×10^{-27}	-0.050	0.793
Earthquake Depth	-5.489	-0.148	0.439
Temporal Delay	-0.886	-0.040	0.832
Distance	-7.487	-0.129	0.496

All variables were not a significant predictor ($p > 0.0005$)

Multiple Regression Equation:

$$y = 1468.887 - (3.154\ x\ 10^{-27})x_1\ - 7.487x_2\ - 5.489x_3 - 0.886x_4 \qquad \text{(Eq. 4.2)}$$

Figures 4.14-4.16 present maps to show the spatial pattern of response at each volcano. Overall, based on Figure 4.8, it can be seen that all earthquake-volcano interactions are located on the Ring of Fire and follow the trend of the adjacent fault line. Within South America, the earthquakes that influence Puyehue-Cordon Caulle and Villarrica are located on the Nazca plate and within close proximity to the fault line (Figure 4.14). In Papua New Guinea, all earthquakes occur on the Indo-Australian plate (Figure 4.15). In particular, the largest influencing earthquakes (M8.1 and M7.6) are located South-East of the responding volcanoes. Finally, Karymsky appears to be influenced by earthquakes that occur along the adjacent fault line (Figure 4.16).

Map removed

Figure 4.14 Spatial pattern of response at Villarrica and Puyehue-Cordon Caulle following a M8.8 and M6.3 earthquake, respectively (Source: ESRI 2009).

Maps removed

Figure 4.15 Spatial pattern of Earthquake-Volcano Interactions, Papua New Guinea (Source: ESRI 2009).

Figure 4.16 Spatial pattern of response at Karymsky to a M6.6 and M6.1 earthquake (Source: ESRI 2009).

4.3 Summary

This chapter has presented the results of this thesis. Firstly, pilot study results were presented and a comparison to the findings of Delle Donne *et al.* (2010) discussed. Based on recommendations from this, results from the extended method were presented and a synopsis of the main patterns and trends provided. The forthcoming chapter will now discuss these results in relation to current literature and propose mechanisms of response.

Chapter 5

Discussion

This chapter will now discuss the results and trends presented in Chapter 4. Each stage of the method will be considered separately. Firstly, a brief overview of the pilot study will be discussed followed by a detailed review of the results from the extended method. Based on this, mechanisms of response will be proposed and evaluated in comparison to the results presented. The methodology will then be critiqued and data sources evaluated. Finally, on review of the results produced and the performance of the methodology, a number of improvements will be suggested.

5.1 Discussion

5.1.1 Pilot Study

As discussed previously (Section 4.1), there are significant differences in the relationships identified by Delle Donne *et al.* (2010) and the results presented in this research. In general, Delle Donne *et al.* (2010) presented statistically significant relationships between factors such as distance and magnitude (0.89); however, re-inspection of these results using only MODVOLC detected thermal anomalies (Pilot Study) produced weaker correlations (0.425). Without knowing reasons for altering the data used, it is important to note that the statistical links between each pair of variables are limited. Whilst Figure 4.3a (pg. 49) demonstrates this, similarities between R^2 values (0.85 and 0.90) suggest that factors such as fault strike direction and volcano azimuth are more indicative of the relationship. In this respect it can be suggested that, based on the evidence provided, claims that fault orientation and azimuth are controlling factors on the relationship are valid.

5.1.2 Review of Delle Donne et al. (2010)

Following a review of the methodology set out by Delle Donne *et al.* (2010), Section 3.3 provides an evaluation of the pilot study and makes a set of recommendations that were incorporated into an extended method. Alongside this, a number of inconsistencies are found relating to the claimed responses. Firstly, the distance between earthquake epicentre and potentially responding volcano had to be within 750 km (Delle Donne *et al.* 2010). In a number of cases, the distance for regional associations exceeded the stated criterion, including earthquake-volcano interactions at the regional and global scale. One particular example includes the eruption of Klyuchevskoi, 8300 km away, following the 2004 Boxing Day earthquake which in addition was not within the 15-day response window. Furthermore, correlations between earthquake magnitude and distance (Figure 4.1b, pg.48) and, earthquake magnitude and response duration (Figure 4.2b, pg.48) incorporated data from a number of secondary sources, negating the use of satellite-derived volcanic heat flux. The correlation between earthquake magnitude and distance, for example, includes findings from previous studies which used historic or observational records (total data points = 68). Whereas the correlation between earthquake magnitude and response duration was based on the 24 volcanoes identified as responding rather than each recorded earthquake-volcano interaction. Thus, it is likely that the relationships derived are, in fact, limited.

Additionally, it was observed that for some interactions identified by Delle Donne *et al.* (2010) the mean radiative power was not twice as high as claimed. An example of this is the response of Santa Maria to a M6.1 earthquake in December 2000. In this instance, the increase in radiative power was only one and a half times the mean radiative power recorded before the earthquake occurrence. With this in mind, it is apparent that future assessments of eruption triggering by volcanoes must establish and maintain a set of stringently applied criteria.

Finally, re-examination of the relationships presented by Delle Donne *et al.* (2010) showed that these results were, in fact, the correlation coefficient (R) and not the R^2 value. In this case, the identification of the correlation coefficient (R) rather than the R^2 value overestimates the strength of the relationship between each variable. As such, it must be considered that the statistical links presented are likely to be unreliable; therefore, further exploratory analysis of earthquake-volcano interactions is warranted.

5.1.3 Extended Method

Phase A illustrates cases of increased radiative power following earthquakes. In particular, there are 12 volcanoes which show the clearest responses (Table 4.3, pg. 51), with a number of interactions showing possible re-awakening of activity. Further inspection of Figures 4.4-4.7 (pg. 51-53) shows that once erupting volcanoes appear to be influenced by smaller magnitude events. This type of triggering is likely to be due to (in part) the critical state (i.e. exsolving gases and magma present) of the volcano (Brodsky *et al.* 1998). Once responding, however, it is surmised that a volcano may be susceptible to subtle changes in stress (resulting from a smaller magnitude event) causing fracturing and shear failure (Kilburn 2003; West *et al.* 2005). Finally, Figure 4.6 (pg. 52) demonstrates periods of activity at Villarrica which are not affected by large earthquakes, providing evidence for the range of other processes also capable of initiating volcanic activity.

Similarly, preliminary results from Phase B identify 36 occurrences where changes in radiative power are experienced following an earthquake. Most notably, it can be seen that for changes in radiative power of more than 100% only increases were recorded[1] (Table 4.4, pg. 54). In particular, Figures 4.9 and 4.10 (pg. 56) depict patterns of response for volcanoes that were quiescent before an earthquake and volcanoes where activity was on-going. Within these graphs, it can be seen that there are short delays between the earthquake occurrence and a volcanoes response. At this point, there is a dramatic change in radiative power which increases sharply during the following month and then stabilises. The largest change in radiative power (1500 MW) was at Puyehue-Cordon Caulle when new activity began following the occurrence of a M6.3 earthquake (Figure 4.9). This is not the first time a response has been recorded at this volcano. Indeed, a M9.5 earthquake in 1960 initiated a response two days following the earthquake (Barrientos 1994). In addition, Figure 5.1 compares the typical response at volcanoes where activity was on-going (Active) and volcanoes where activity was not present before an earthquake (Not Active). In particular, responses at non-active volcanoes tend to experience larger increases in radiative power following an earthquake compared to active volcanoes.

[1] While changes in radiative power of more than 50% recorded cases of decreased activity, only changes of more than 100% were examined in this thesis due to the similar results obtained and the identification of this threshold by previous research.

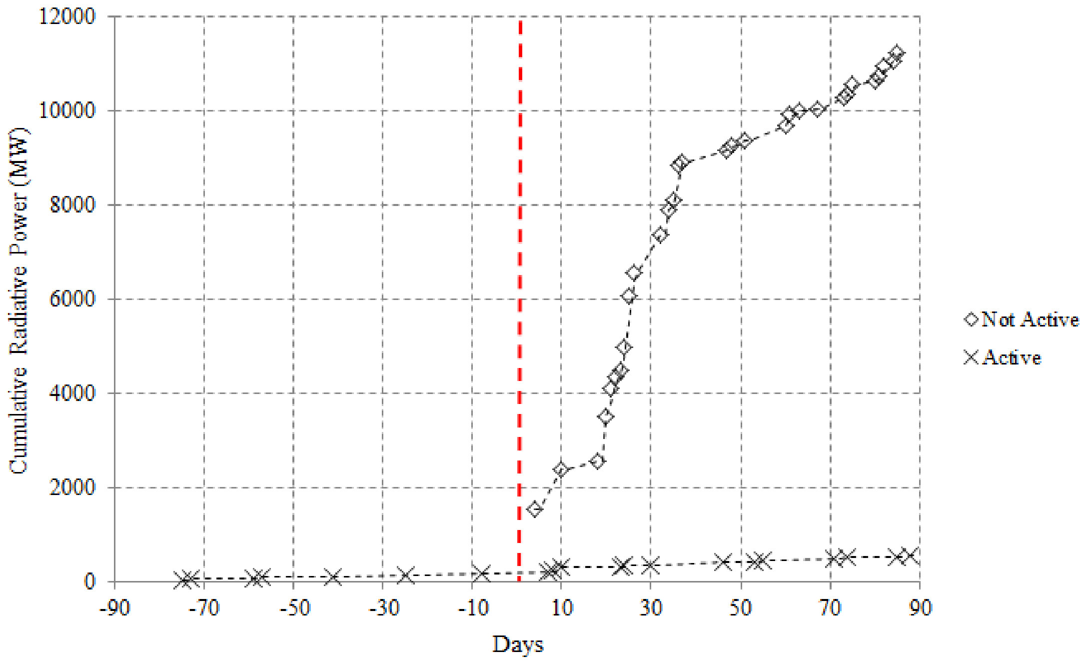

Figure 5.1 Comparison of Active and Not Active volcanic responses where the earthquake occurrence is depicted by the red dashed line.

In contrast, statistical analyses between pairs of variables (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance) found no statistically significant relationships (Table 4.5, pg. 57). The strongest relationship (0.09) was between earthquake depth and distance to responding volcano. Although still relatively weak, Figure 4.11 (pg. 58) shows that the majority of influencing earthquakes are shallow focus events (Depth≤60 km). In particular, it can be noted that shallower earthquakes tend to trigger responses at larger distances with the optimum range of response being between 200 and 800 km (Figure 4.11) compared to 100-200 km identified by Marzocchi *et al.* (2004). In addition, there are two further responses to earthquakes at depths of 132 km and 186 km. Despite these interactions being identified as possible anomalies, their occurrence is validated based on the findings of Walter *et al.* (2007) who demonstrated that deep focus events are also capable of initiating a response.

Figures 4.12 and 4.13 (pg. 58-59) demonstrate the effect that earthquake magnitude and depth have on temporal delay. Generally, there are no statistical relationships (0.05 and 0.03, respectively) between these variable pairs. In particular, it is suggested that the delayed responses (of up to 50 days) reflect the time it takes for changes within the magma chamber to reach the earth's surface (Hill *et al.* 2002; Walter and Amelung 2006; Harris and Ripepe 2007; Delle Donne *et al.* 2010). Furthermore, Figure 4.12 identifies that smaller magnitude events (M≤7.0) have shorter temporal delays contradicting previous work which suggested that large earthquakes (M≥7.0) are a controlling factor on response time (Acharya 1982).

Table 4.6 (pg. 60) shows the results of the multiple regression analysis on change in radiative power. Overall, there are no statistically significant relationships between each predictor variable and change in radiative power, further confirming the findings of Table 4.5 (pg. 57). In particular, it is shown that these variables account for less than 10% of the variation and, as a result, it can be suggested that there are a number of other external factors, such as the state of the magma chamber and fault strike direction (Brodsky *et al.* 1998; Harris and Ripepe 2007; Delle Donne *et al.* 2010), which may have a larger influence on the response of volcanoes to earthquakes.

Indeed, one key factor identified to be gaining emphasis within this field is the effect of site specific volcano characteristics. At its broadest level, it can be suggested that each volcano has a number of conditions and, therefore triggering thresholds, which need to be met for a response to occur (Darwin 1840; Barrientos 1994; Sturtevant *et al.* 1996; Brodsky and Prejean 2005). Alongside this, there are a number of cases where earthquakes have been recognised to modify eruption characteristics (Power *et al.* 2001; La Femina *et al.* 2004; Walter and Amelung 2007). Arguably, these observations demonstrate that the variables under study in thesis do not account for the variability that may be experienced between different regions or sites, therefore, depending on the volcanic system (volcano type, eruption history, eruption style and size), volcanoes may be more (or less) susceptible to triggering.

Spatial analyses showed that all earthquake-volcano interactions occur along the Pacific 'Ring of Fire' and are located on convergent plate boundaries (Figures 4.14-4.16, pg. 61-62). Within South America, the boundary marks the subduction of the Nazca plate below the South American Plate. Here, the earthquakes are located on the subducting plate (Nazca) and the responding volcanoes are located to the South-East on the overriding plate (South American). In Papua New Guinea all earthquake-volcano interactions occur on the same plate (Indo-Australian). In this instance, the Indo-Australian plate is overriding the Pacific plate which is subducting below. What is more, all responding volcanoes are located within close proximity to each other and a number of earthquakes are noted to trigger more than one volcanic response. It is surmised by Eggert and Walter (2009) and

Watt *et al.* (2009) that these coupled responses reflect the increased susceptibility of sub-regions, particularly volcanic arcs, to triggering due to the stress changes associated with large seismic events. Finally, Karymsky appears to respond to two earthquakes which are located on the same fault plane. This zone of subduction (the Pacific plate subducting below the North American and Okhotsk plates), provides evidence for mechanisms such as rupture directivity resulting from the propagation of seismic waves and may explain why a response does not always occur (Delle Donne *et al.* 2010).

In addition, at the global scale, all volcanoes occurred on the landward side of the earthquake epicentre. First noted by Acharya (1982), it can be suggested that position over the subducting plate may be an influential factor on whether a response will occur. In particular, the Benioff zone (Figure 5.2) reflects a zone of active seismicity which is marked by volcanic arcs on the earth’s surface (Bryant 2005). As a result, earthquake-volcano interactions in this zone may be due to changes in stress resulting from an earthquake (Bryant 2005).

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Figure 5.2 Benioff zone within a convergent plate boundary (Source: Bryant 2005: 185).

On review of these findings, a number of causal mechanisms can be proposed. Firstly, Walter and Amelung (2007) suggested a mechanism of volumetric expansion. During an earthquake, it is suggested that the build-up of stress located around a seismic zone (10-50 km below the earth’s surface) initiates a process of volumetric expansion beneath the volcano (Figure 5.3). This increase in pressure within the magma chamber initiates an eruption stabilising the stress changes that have taken place and, in some cases, modifies the eruption sequence.

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Figure 5.3 Areas of volumetric contraction (blue) and expansion (red) associated with large seismic events (Source: Walter and Amelung 2007: 541).

The state of the volcanic system has also been recognised as a critical factor in determining whether a response will occur (Barrientos 1994; Brodsky *et al.* 1998; Harris and Ripepe 2007). As a result, it is possible that mechanisms such as rectified diffusion act within the magma chamber (Sturtevant *et al.* 1996; Brodsky *et al.* 1998). Here, the passage of seismic waves are suggested to excite bubbles within the magma causing overpressure and resulting in an eruption (Brodsky *et al.* 1998).

In contrast, Delle Donne *et al.* (2010) suggested that fault characteristics and rupture directivity are controlling factors in triggering a response. As discussed previously, rupture directivity results from the concentration of wave energy along the fault rupture and, as a result the direction of propagation is always greater along a certain path (Delle Donne *et al.* 2010; USGS 2012c). In addition, it is suggested that rather than distance to earthquake epicentre, distance to earthquake rupture zone may favour a response due to the capabilities of large earthquakes ($M \geq 8.0$) to rupture over 100 km of the fault line (Brodsky *et al.* 1998).

As indicated by each of these proposed mechanisms, changes in stress resulting from the passage of seismic waves appear key in the triggering process. In particular, Hill *et al.* (2002) surmised that changes in stress (static, dynamic and viscoelastic) are capable of triggering a number of mechanisms. Further adding that it is reasonable to assume any mechanism could initiate a response providing the volcano was in a favourable state (Hill *et al.* 2002). Alternatively, it is suggested that the coupling of these two hazards is an indirect consequence where the build-up of static stress induces an earthquake and the resulting stress changes (stress diffusion) promote a volcanic response (Marzocchi *et al.* 2002; Marzocchi *et al.* 2004; Walter 2007).

Building on theories of favourable volcanic systems, it has also been proposed that permanent stress changes, resulting from an earthquake, trigger volcanic unrest by increasing the pressure on the magma chamber or initiating a series of induced-fluid dynamic changes (Barrientos 1994; Marzocchi 2002; Walter and Amelung 2006; Delle Donne *et al.* 2010). In particular, at large distances (up to 1000 km), dynamic stress changes are capable of accelerating unrest at volcanoes in a pre-eruptive state (Watt *et al.* 2009; Delle Donne *et al.* 2010).

Overall, it is evident that the relationship between earthquakes and volcanoes is still unclear. While preliminary results illustrate cases of increased radiative power directly following an earthquake, more detailed analyses find no statistical relationships. In contrast, patterns identified in spatial analyses indicated that physical mechanisms due to changes in stress may be more indicative of the relationship. Fault characteristics and the passage of seismic waves thus provide an insight into why only certain volcanoes respond and why earthquakes alone may not be capable of triggering an eruption. In addition, a set of common factors, such as volcanoes in a favourable state and magma body disturbance, need to be met for a volcano to respond. As a result, it can be suggested that the variables under study in this thesis (earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance) are secondary causative factors which contribute towards the relationship and that physical changes resulting from an earthquake are the main trigger promoting a response.

5.2 Evaluation

While the method set out in Chapter 3 was successfully implemented, there were a number of factors which limited its ability to define the relationship between earthquakes and volcanoes. Firstly, the use of thermal anomaly detection systems meant that other indicators of volcanic activity were not examined. Although thermal anomaly detections provide a valuable means to quantify volcanic eruptions (Wiesnet and D'Aguanno 1982; Harris and Ripepe 2007; Delle Donne *et al.* 2010), there are a number of alternative indicators (ash clouds, seismicity and deformation) of volcanic activity and unrest (McNutt 1996; Chastin and Main 2003; Pritchard and Simons 2004; Webley *et al.* 2009). As a result, it can be suggested that the response of volcanoes to earthquakes may undergo more complex interactions than identified by thermal anomaly data alone. In order to overcome this, seismic and deformation (InSAR) datasets could be used to monitor physical changes at volcanoes following an earthquake (McNutt 2002; Fournier *et al.* 2010; Pritchard *et al.* 2011). Overall, this would help improve change detection techniques and may, in addition, identify more subtle responses.

On review of the proposed mechanisms, it was evident that factors such as fault orientation and rupture zone may be more indicative of the influencing earthquake during periods of continued seismicity (Brodsky *et al.* 1998; Delle Donne *et al.* 2010). Based on this, fault characteristics, the propagation of seismic waves and surrounding earth surface characteristics could be incorporated into investigations to determine the physical changes that take place and accurately identify the triggering event. In particular, Walters *et al.* (2011) demonstrated that strain measurements could be used to measure interseismic deformation across the North Anatolian Fault, an approach which could be equally applied to measure stress changes around a volcano following an earthquake. Overall, these additional datasets would allow mechanisms such as rupture directivity and rectified diffusion to be analysed and may indicate more significant interactions.

The response window, in addition, presented limitations. Despite the majority of responses resulting in an increase in volcanic activity, it is possible that an earthquake was misidentified as a trigger. The lack of any statistically significant relationship, therefore, supports the argument that the clustering of seismic and volcanic activity may be due to chance (Power *et al.* 2001). The long response times indicated by Hill *et al.* (2002), however, suggests that the onset of activity may first begin with volcanic unrest (increased seismicity and degassing), culminating in an eruption several years after the original onset of activity (McNutt 2002; Pritchard and Simons 2004; Magna and Brodsky 2006). A priority, therefore, is to establish long-term volcanic activity so that all triggered responses can be recognised.

Equally, cumulative seismic energy release may play a key role in triggering (Blot 1965; Latter 1971; Cigolini *et al.* 2007). Put simply, it is suggested that a sequence of regional earthquakes may trigger volcanic unrest. This can result from a deep focused event initiating a number of smaller interactions which results in unrest; or, a cluster of small magnitude earthquakes initiating the same processes as a single large magnitude event

(Latter 1971; Brodsky *et al.* 1998; Brodsky and Prejean 2005; Cigolini *et al.* 2007). In this respect, it is apparent that future investigations of eruption triggering must first establish whether the triggering event resulted from a single large magnitude event or a series of smaller magnitude earthquakes.

In addition, an evaluation of data sources and data quality allows their utility to earthquake-volcano studies to be established. The different algorithms used by MODVOLC and MOD14 means that each dataset has its own advantages and limitations. In particular, MODVOLC detects significantly more thermal anomalies than MOD14, however, the capabilities of MOD14 to detect lower temperature anomalies means that this algorithm is more appropriate to measure low-level volcanic activity. Alongside this, volcanic islands and the presence of clouds meant that there were a number of missed detections by MOD14 (discussed in Section 4.2.2). Alternative thermal hotspot detection systems or a combined MOD14-MODVOLC approach, therefore, could be used to improve detection. In particular, a combined MOD14-MODVOLC approach would allow the optimum number of thermal anomalies to be detected; currently however, there is no defined method for such an approach.

In contrast, the USGS NEIC seismic record presented few limitations. However, considering the proposed mechanisms of response discussed in this thesis, it is evident that further investigations which examine earthquake and fault characteristics would need to use a number of alternative datasets to obtain information on factors such as fault azimuth.

Finally, the effect of volcanic activity on earthquakes, as discussed in Section 1.3, was not considered. Figure 5.4, in particular, demonstrates the occurrence of a M7.6 earthquake following the eruption of Pago in August 2002. While discussed in previous research (Nostro *et al.* 1998; Moran *et al.* 2002; Eggert and Walter 2009), less attention has been given to this ‘reverse’ relationship. As a result, future investigations could examine the two-way coupling of the relationship at volcanoes with the strongest earthquake-volcano interactions.

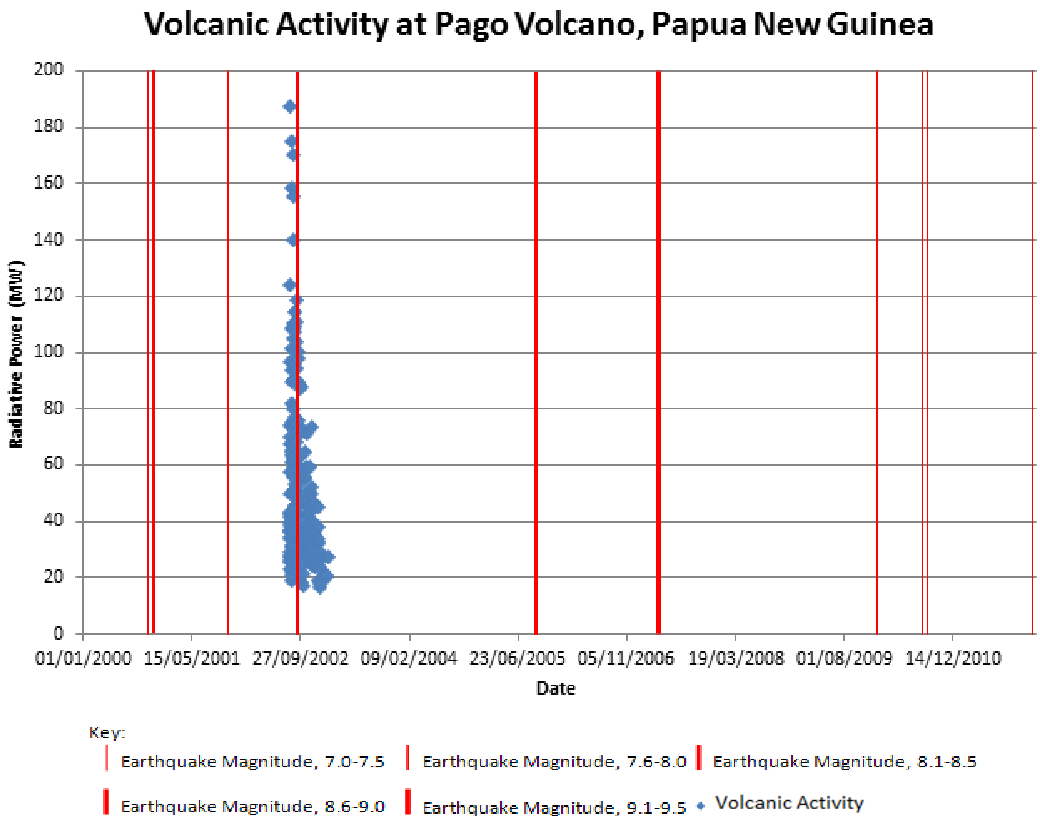


Figure 5.4 Two-way coupling of earthquakes and volcanoes demonstrated by the occurrence of a M7.6 earthquake after the eruption of Pago in August 2002.

5.3 Summary

This chapter has discussed the main findings and patterns in relation to current literature and proposed mechanisms of response, satisfying Objective 5 (Section 1.5). Table 5.1 summarises these proposed mechanisms as well as documenting the main parameters that affect them. Furthermore, by considering the evidence presented in this thesis, it is apparent that changes in stress and the state of the volcanic system are important factors which will determine whether a response will occur. While it is apparent that the variables under study in this thesis do not explain the relationship, the utility of satellite remote sensing to study earthquake-volcano interactions, subject to the limitations discussed in Section 5.2, has been demonstrated.

Table 5.1 Summary of proposed mechanisms of response based on findings in this thesis.

Mechanism of Response	Description	Influencing Parameters	Previous Research
Rupture Directivity	Concentration of seismic waves along a fault.	➢ Propagation of seismic waves	Hill *et al.* (1993) Brodsky *et al.* (1998) Husen *et al.* (2004a) Magna and Brodsky (2006) Cigolini *et al.* (2007) Delle Donne *et al.* (2010)
Volumetric Expansion	Build-up of stress around a fault initiates a process of volumetric contraction in the near trench and volumetric expansion beneath a volcano. Overpressure within the magma chamber results in an eruption.	➢ Stress changes resulting from an earthquake	Walter and Amelung (2007)
Rectified Diffusion	Excitation of bubbles within the magma chamber causes overpressure culminating in an eruption.	➢ Passage of seismic waves through the magma chamber	Sturtevant *et al.* (1996) Brodsky *et al.* (1998)

Chapter 6

Conclusion

At present, the relationship between earthquakes and volcanic activity provides vital clues for volcanic activity prediction and the identification of potential precursors. Despite this, the results of this thesis do not support any one mechanism of response. While preliminary findings documented increases in radiative power directly following a regional earthquake, more detailed analyses found no statistical relationships between different variable pairs. In contrast, spatial analyses were found to support previous research which identified relationships between physical indicators. Based on this, it is suggested that the relationship between earthquakes and volcanoes is based on physical processes promoting activity and unrest.

What is more, re-examination of work by Delle Donne *et al.* (2010) found that the methodology and results presented have a number of inconsistencies. Although concluding remarks which suggest rupture directivity as a possible trigger are appropriate, this research could not corroborate the findings presented. Hence, it is advisable that the results presented should be treated with caution. In this regard, recommendations for further research have been outlined throughout this thesis and it is suggested that in applying such methods, criteria for analysis should be clearly identified.

Considering this, it is apparent that changes in stress are the probable cause of response. Similarities between proposed mechanisms suggest that responses are constrained by the physical interactions between earthquakes and volcanoes. In particular, it is possible that more than one mechanism is capable of triggering volcanic activity with global factors controlling whether a response occurs and sub-regional influences determining the triggering mechanism. In addition, the state of the magma chamber, the passage of seismic waves and fault characteristics have been identified as factors which contribute towards the relationship.

As discussed previously, a detailed knowledge and understanding of volcanic precursors provides key benefits to volcanic hazard management and response (Harris and Ripepe 2007). As such, it is apparent that the identification of any relationship between earthquakes and volcanoes will enable computational forecast models to be designed and implemented. While the results of this research impede the development of any forecast model, it is possible that future investigations to identify factors that result in a response could identify the use of earthquakes as a precursory indicator to volcanic activity. In addition, investigations at a wider scale or over a longer time period could aid the design and implementation of a volcano early warning system as well as providing valuable information on the relationship between earthquakes and volcanic activity and the factors that cause it.

In conclusion, this thesis has investigated the effect that earthquake magnitude, earthquake depth, change in radiative power, temporal delay and distance have on the relationship between earthquakes and volcanoes, satisfying the aims and objectives set out in Section 1.5. Overall, evidence presented in this thesis supports a relationship; however, the variables under study do not explain its existence. Coupled with this, this thesis has demonstrated that previous research within the field does not stand up to analysis. As such, investigations of recent large earthquakes, for example the M7.4 earthquake in Mexico (March 2012), could provide additional clues on the relationship. With this in mind, it is apparent that the identification of any relationship would provide valuable information of the interactions between earthquakes and volcanoes.

6.1 Recommendations for Further Research

On review of the findings presented in this thesis, it is suggested that future research in this field should focus on physical processes of response. Consequently, research is required to address the effect of each proposed mechanism on different earthquake-volcano interactions. For example, it is possible that shallow focus earthquakes cause different physical changes to deep focus events. In essence, this approach would allow the forcing mechanisms within a system to be identified and, as a result, favourable conditions could be defined that outline the potential for response. To gauge the effect of the relationship at different scales, repeat investigations at sub-regional and global scales could be conducted to determine the role of stress transfer. Indeed, similar studies of volcano specific interactions have extended the knowledge basin as well as providing vital clues on the relationship (Walter 2007). Further work could now conduct a detailed remote sensing investigation to examine the thermal and physical response of volcanoes to earthquakes. By establishing a set of common factors which contribute towards the relationship, it may be possible to attribute a mechanism of response which will aid emergency planning and response.

Chapter 7

References

Acharya, H. (1982) ‘Volcanic activity and large earthquakes’. *Journal of Volcanology and Geothermal Research* 13, 373-378

Acharya, H. (1987) ‘Spatial Changes in Seismic and Volcanic Activity Prior to Great Earthquakes’. *Pure and Applied Geophysics* 125 (6), 1097-1118

Agustan; Kimata, F.; Pamitro, Y. E. and Abidin, H. (2012) ‘Understanding the 2007-2008 eruption of Anak Krakatau Volcano by combining remote sensing technique and seismic data’. *International Journal of Applied Earth Observation and Geoinformation* 14, 73-82

Alam, M. M. and Kimura, M. (2004) ‘Statistical analysis of time-distance relationship between volcanic eruptions and great earthquakes in Japan’. *Earth Planets Space* 56, 179-192

Alam, M. M; Katao, H.; Kumar, A. and Kimura, M. (2010) ‘Relationship Between Major Eruptions and Large Earthquakes: A Comparative Study Between Japan and Indonesia’. *Annuals of Disaster Prevention Research Institute* 53, 1-8

Alexander, D. (2001) *Natural Disasters.* Florida: CRC Press

Barrientos, S. E. (1994) ‘Large Thrust Earthquakes and Volcanic Eruptions’. *Pure and Applied Physics* 142 (1), 225-237

Berk, A.; Bernstein, L. S. and Robertson, D. C. (1989) ‘MODTRAN: A Moderate Resolution Model for LOWTRAN7’. *Air Force Geophysical Laboratory*

Berk, A.; Bernstein, L. S.; Anderson, G. P.; Acharya, P. K.; Robertson, D. C.; Chetwynd, J. H. and Adler-Golden, S. M. (1998) ‘MODTRAN Cloud and Multiple Scattering Upgrades with Application to AVIRIS’. *Remote Sensing of Environment* 65, 367-375

Blackett, M. (2009) *An Investigation into the Detection and Analysis of Potential Surface Thermal Anomalies associated with Terrestrial Volcanoes and Earthquakes using EOS and Other Post-2000 Satellite Observations*. Unpublished PhD Thesis. London: King's College London

Blackett, M.; Wooster, M. J. and Malamud, B. (2011) 'Exploring claims of land surface temperature precursors to the 2001 Gujarat earthquake'. *Geophysical Research Letters* 38, 1-7

Blot, C. (1965) 'Relationship between deep earthquakes and volcanic eruptions in Japan'. *Volcanological Bulletin* 28 (1), 25-63

Brenguier, F.; Shapiro, N. M.; Campillo, M.; Ferrazzini, V.; Duputel, Z.; Coutant, O. and Nercessian, A. (2008) 'Toward Forecasting Volcanic Eruptions using Seismic Noise'. *Nature Geoscience* 1, 126-130

Brodsky, E. E.; Sturtevant, B. and Kanamori, H. (1998) 'Earthquake, volcanoes, and rectified diffusion'. *Journal of Geophysical Research* 103 (10), 23,827-23,838

Brodsky, E. E. and Prejean, S. G. (2005) 'New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera'. *Journal of Geophysical Research* 110, 1-14

Bryant, E. (2005) *Natural Hazards*. Cambridge: Cambridge University Press

Cardoso, M. F.; Hurtt, G. C.; Moore III, B.; Nobre, C. A. and Bain, H. (2005) 'Field work and statistical analyses for enhanced interpretation of satellite fire data'. *Remote Sensing of Environment* 96, 212-227

Carr, M. J. (1977) 'Volcanic activity and great earthquakes at convergent plate margins.' *Science* 197, 655-657

Chastin, S. F. M. and Main, I. G. (2003) 'Statistical analysis of daily seismic event rate as a precursor to volcanic eruptions'. *Geophysical Research Letters* 30 (13), 1-4

Christopherson, R. W. (2006) *Geosystems.* USA: Pearson Preston Hall

Cigolini, C.; Laiolo, M. and Coppola, D. (2007) 'Earthquake-volcano interactions detected from radon degassing at Stromboli (Italy)'. *Earth and Planetary Science Letters* 257, 511-525

Coch, N. K. (1995) *Geohazards: Natural and Human*. London: Prentice-Hall

Collombet, M.; Grasso, J-R. and Ferrazzini, V. (2003) 'Seismicity rate before eruptions on Piton de la Fournaise volcano: Implications for eruption dynamics'. *Geophysical Research Letters* 30 (21), 1-5

Coppola, D.; Piscopo, D.; Laiolo, M.; Cigolini, C.; Delle Donne, D. and Ripepe, M. (2012) 'Radiative power at Stromboli volcano during 2000-2011: Twelve years of MODIS observations'. *Journal of Volcanology and Geothermal Research* 215-216, 48-60

Darwin, C. (1840) 'On the connexion of certain volcanic phenomena in South America; and on the formation of mountain chains and volcanoes, as the effect of the same power by which continents are elevated'. *Geological Society Transactions* 2, 601-632

Davies, R. J.; Brumm, M.; Manga, M.; Rubiandini, R.; Swarbrick, R. and Tingay, M. (2008) 'The East Java Mud Volcano (2006 to Present): An Earthquake or Drilling Trigger?'. *Earth and Planetary Science Letters* 272 (3-4), 627-638

Decker, R. W. (1986) 'Forecasting Volcanic Eruptions'. *Annual Review of Earth Planetary Science* 14, 267-291

De la Cruz-Reyna, S.; Tárraga, M.; Ortiz, R. and Martínez-Bringas, A. (2010) 'Tectonic earthquakes triggering volcanic seismicity and eruptions. Case studies at Tungurahua and Popocatépetl volcanoes'. *Journal of Volcanology and Geothermal Research* 193, 37-48

Dehn, J.; Dean, K. and Engle, K. (2000) 'Thermal monitoring of North Pacific volcanoes from space'. *Geology* 28 (8), 755-758

Delle Donne, D.; Harris, A. J. L.; Ripepe, M. and Wright, R. (2010) 'Earthquake-induced thermal anomalies at active volcanoes'. *Geology* 38 (9), 771-774

Di Bello, G.; Filizzola, C.; Lacava, T.; Marchese, F.; Pergola, N.; Pietrapertosa, C.; Piscitelli, S.; Scaffidi, I. and Tramutoli, V. (2004) ‘Robust satellite techniques for volcanic and seismic hazards monitoring’. *Annals of Geophysics* 47 (1), 49-64

Dzierma, Y. and Wehrmann, H. (2010) ‘Statistical eruption forecast for the Chilean Southern Volcanic Zone: typical probabilities of volcanic eruptions as baseline for possibly enhanced activity following the large 2010 Concepción earthquake’. *Natural Hazards and Earth System Sciences* 10, 2093-2108

Eggert, S. and Walter, T. R. (2009) ‘Volcanic activity before and after large tectonic earthquakes: Observations and statistical significance’. *Tectonophysics* 1-13

EM-DAT (2012a) *Final Results for Request EM-DAT* [online] available from <http://www.emdat.be /final-result-request> [19th May 2012]

EM-DAT (2012b) *Natural Disaster Trends EM-DAT* [online] available from <http: //www.emdat.be/natural-disasters-trends> [19th May 2012]

ESRI (2009) *World Physical Map*. ESRI

Flynn, L.; Wright, E.; Garbeil, H.; Harris, A. and Pilger, E. (2002) ‘A global thermal alert system using MODIS: Initial results from 2000-2001’. *Advances in Environmental Monitoring and Modelling* 1 (1), 37-69

Fournier, T. J.; Pritchard, M. E. and Riddick, S. N. (2010) ‘Duration, magnitude, and frequency of subaerial volcano deformation events: New results from Latin America using InSAR and a global synthesis’. *Geochemistry Geophysics Geosystems* 11 (1), 1-29

Francis, P. W. and McAllister, R. (1986) ‘Volcanology From Space: Using Landsat Thematic Mapper Data in the Central Andes’. *EOS Transactions American Geophysical Union* 67 (14), 170-171

Francis, P. W. and Rothery, D. A. (1987) ‘Using the Landsat Thematic Mapper to detect and monitor active volcanoes: An example from Lascar volcano, northern Chile’. *Geology* 15, 614-617

Freed, A. M. (2005) ‘Earthquake Triggering by Static, Dynamic, and Postseismic Stress Transfer’. *Annual Review of Earth and Planetary Sciences* 33, 335-367

Gawarecki, S. J.; Lyon, R. J. P. and Nordberg, W. (1965) 'Infrared spectral returns and imagery of the Earth from Space and their application to geological problems: scientific experiments for manned orbital flight.' *American Astronautical Society, Science and Technology Series* 4, 13-133

Giglio, L. (2010) *MODIS Collection 5 Active Fire Product User's Guide Version 2.4*. [online] available from <http://www.fao.org/fileadmin/templates/gfims/docs/MODIS_Fire_Users_Guide_2.4.pdf> [20th July 2012]

Giglio, L.; Descloitres, J.; Justice, C. O. and Kaufman, Y. J. (2003) 'An Enhanced Contextual Fire Detection Algorithm for MODIS'. *Remote Sensing of Environment* 87, 273-282

Glaze, L.; Francis, P. W. and Rothery, D. A. (1989) 'Measuring thermal budgets of active volcanoes by satellite remote sensing'. *Nature* 338, 144-146

Gresta, S.; Ghisetti, F.; Privitera, E. and Bonanno, A. (2005) 'Coupling of eruptions and earthquakes at Mt. Etna (Sicily, Italy): A case study from the 1981 and 2001 events'. *Geophysical Research Letters* 32, 1-4

Harris, A. J. L.; Butterworth, A. L.; Carlton, R. W.; Downey, I.; Miller, P.; Navarro, P. and Rothery, D. A. (1997) 'Low-cost volcano surveillance from space: cast studies from Etna, Krafla, Cerro Negro, Fogo, Lascar and Erebus'. *Bulletin of Volcanology* 59, 49-64

Harris, A. J. L. and Ripepe, M. (2007) 'Regional earthquake as a trigger for enhanced volcanic activity: Evidence from MODIS thermal data'. *Geophysical Research Letters* 34, 1-6

Hawbaker, T. J.; Radeloff, V. C.; Syphard, A. D.; Zhu, Z. and Stewart, S. I. (2008) 'Detection rates of the MODIS active fire product in the United States'. *Remote Sensing od Environment* 112, 2656-2664

Helmstetter, A. (2003) 'Is Earthquake Triggering Driven by Small Earthquakes?'. *Physical Review Letters* 91 (5), 1-5

HIGP (2012) *MODIS THERMAL ALERTS VERSION 2.0* [online] available from <http://modis.higp.hawaii.edu/cgi-bin/modis/modis new.cgi> [last accessed 26th March 2012]

Hill, D. P.; Reasenberg, P. A.; Michael, A.; Arabas, W. J.; Beroza, G.; Brumbaugh, D.; Brune, J. N.; Castro, R.; Davis, S.; dePolo, D.; Ellsworth, W. L.; Gomberg, J.; Harmsen, S.; House, L.; Jackson, S. M.; Johnston, M. J. S.; Jones, L.; Keller, R.; Malone, S.; Munguia, L.; Nava, S.; Walter, J. C.; Wong, V.; Zollweg, J. (1993) 'Seismicity Remotely Triggered by the Magnitude 7.3 Landers, California, Earthquake'. *Science* 260 (5114) 1617-1623

Hill, D. P.; Johnston, J. S.; Langbein, J. O. and Bilham, R. (1995) 'Response of Long Valley caldera to the M_w = 7.3 Landers, California, Earthquake'. *Journal of Geophysical Research* 100 (7) 12,985-13,005

Hill, D. P.; Pollitz, F. and Newhall, C. (2002) 'Earthquake-Volcano Interactions'. *Physics Today* 55 (11) 41-47

Huppert, H. E. and Sparks, R. S. J. (2006) 'Extreme natural hazards: population growth, globalization and environmental change'. *Philosophical Transactions of The Royal Society* 364, 1875-1888

Husen, S.; Taylor, R.; Smith, R. B. and Healser, H. (2004a) 'Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone National Park produced by the 2002 M 7.9 Denali fault earthquake, Alaska'. *Geology* 32 (6), 537-540

Husen, S.; Wiemer, S. and Smith, R. B. (2004b) 'Remotely Triggered Seismicity in the Yellowstone National Park Region by the 2002 M_w 7.9 Denali Fault Earthquake, Alaska'. *Bulletin of Seismological Society of America* 94 (6), 317-331

Johnston, M. J. S.; Hill, D. P.; Linde, A. T.; Langbein, J. and Bilham, R. (1995) 'Transient Deformation during Triggered Seismicity from the 28 June 1992 M_w = 7.3 Landers Earthquake at Long Valley Volcanic Caldera, California'. *Bulletin of Seismological Society of America* 85 (3), 787-795

Justice, C. O.; Giglio, L.; Korontzi, S.; Owens, J.; Morisette, J. T.; Roy, D.; Descloitres, J.; Alleaume, S.; Petitcolin, F. and Kaufman, Y. (2002) 'The MODIS fire products' *Remote Sensing of Environment* 83, 244-262

Kafka, A. L. (2002) 'Statistical analysis of the hypothesis that seismicity delineates areas where future large earthquakes are likely to occur in the central and eastern United States'. *Seismological Research Letters* 1-30

Kaneko, T.; Yasuda, A.; Ishimaru, T.; Takagi, M.; Wooster, M. J. and Kagiyama, T. (2002) 'Satellite Hot Spot Monitoring of Japanese Volcanoes: A Prototype AVHRR-based System'. *Advances in Environmental Monitoring and Modelling* 1 (1), 125-133

Kaufman, Y. J.; Justice, C.; Flynn, L.; Kendall, J.; Prins, E.; Ward, D. E.; Menzel, P. and Setzer, A. (1998) 'Monitoring Global Fires from EOS-MODIS'. *Journal of Geophysical Research* 103, 32,215-32,238

Kervyn, M.; Harris, A. J. L.; Belton, F.; Mbede, E.; Jacobs, P. and Ernst, G. G. J. (2006) *MOLDEN: A semi-automatic algorithm for monitoring small-scale thermal activity at Oldoinyo Lengai Volcano, Tanzania.* 'International Association for Mathematical Geology 11th International Congress' held 3-8 September 2006 at University of Liège, Belgium

Kilburn, C. R. J. (2003) 'Multiscale fracturing as a key to forecasting volcanic eruptions'. *Journal of Volcanology and Geothermal Research* 125, 271-289

Kimura, M. (1976) 'Major magmatic activity as a key to predicting large earthquakes along the Sagami Trough, Japan'. *Nature* 260, 131-133

Koeppen, W. C.; Pilger, E. and Wright, R. (2011) 'Time series analysis if infrared satellite data for detecting thermal anomalies: a hybrid approach'. *Bulletin of Volcanology* 73, 577-593

La Femina, P. C.; Connor, C. B.; Hill, B. E.; Strauch, W. and Saballos, J. A. (2004) 'Magma-Tectonic interactions in Nicaragua: the 1999 seismic swarm and eruption of Cerro Negro volcano'. *Journal of Volcanology and Geothermal Research* 137, 187-199

Lacava, T.; Coviello, I.; Marchese, F.; Mazzeo, G.; Pergola, N.; Tramutoli, V. (2010) *A preliminary comparison of RST and MODVOLC techniques for satellite monitoring of thermal volcanic activity.* 'EGU General Assembly'. held May 2010 in Vienna, Austria.

Latter, J. H. (1971) 'The Interdependence of Seismic and Volcanic Phenomena: Some Space – Time Relationships in Seismicity and Volcanism'. *Bulletin of Volcanology* 35 (1), 127-142

Lemarchand, N. and Grasso, J-R. (2007) 'Interactions between earthquakes and volcanic activity'. *Geophysical Research Letters* 34, 1-5

Linde, A. T. and Sacks, I. S. (1998) 'Triggering of volcanic eruptions'. *Nature* 395,888-890

MacGregor, A. G. (1949) 'Prediction in relation to Seismo-volcanic Phenomena in the Caribbean Volcanic Arc' *Bulletin of Volcanology* 8 (1), 69-86

Magna, M. and Brodsky, E. (2006) 'Seismic triggering of eruptions in the far field: Volcanoes and geysers'. *Annual Review Earth Planetary Science* 34, 263-291

Marchese, F.; Pergola, N. and Tramutoli, V. (2006) *An automatic satellite monitoring system for volcanic hazard monitoring in near real-time.* 'European Geosciences Union General Assembly' held 2-7 April 2006 at Vienna, Austria

Marzocchi, W. (2002) 'Remote seismic influence on large explosive eruptions'. *Journal of Geophysical Research* 107 (1), 1-7

Marzocchi, W.; Casarotti, E. and Piersanti, A. (2002) 'Modeling the stress variations induced by great earthquakes on the largest volcanic eruptions of the 20^{th} century'. *Journal of Geophysical Research* 107 (11), 1-8

Marzocchi, W.; Zaccarelli, L. and Boschi, E. (2004) 'Phenomenological evidence in favor of a remote seismic coupling for large volcanic eruptions'. *Geophysical Research Letters* 31, 1-5

Mason, B. G.; Pyle, D. M.; Dade, W. B. and Jupp, T. (2004) 'Seasonality of volcanic eruptions'. *Journal of Geophysical Research* 109, 1-12

McNutt, S. R. (1996) 'Seismic monitoring and eruption forecasting of volcanoes: A review of the state-of-the-art and case histories'. ed. by Scarpa, R. and Tilling, R.. New York: Springer 99-146

McNutt, S. R. (2002) ‘Volcano Seismology and Monitoring for Eruptions’. ed. by Lee, W. H. K.; Kanamori, H. and Jennings, P. C.. London: Academic Press

Moran, S. C.; Stihler, S. D. and Power, J. A. (2002) ‘A tectonic earthquake sequence preceding the April-May 1999 eruption of Shishaldin Volcano, Alaska’. *Bulletin of Volcanology* 64, 520-524

Morisette, J. T.; Giglio, L.; Csiszar, I.; Setzer, A.; Schroeder, W.; Morton, D. and Justice, C. O. (2005) ‘Validation of MODIS Active Fire Detection Products Derived from Two Algorithms’. *Earth Interactions* 9, 1-25

Nakamura, K. (1977) ‘Volcanoes as possible indicators of tectonic stress orientations – principle and proposal’. *Journal of Volcanology and Geothermal Research* 2, 1-16

NASA Earth Observatory (2004) *Sensing remote volcanoes: Feature article* [online] available from < http://earthobservatory.nasa.gov/Features/monvoc/printall.php> [17th May 2012]

Nostro, C.; Stein, R. S.; Cocco, M.; Belardinelli, M. E. and Marzocchi, W. (1998) ‘Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes, Italy, by elastic stress transfer’. *Journal of Geophysical Research* 103, 24,424-24,487

Pergola, N.; Marchese, F.; Tramutoli, V.; Filizzola, C. and Ciampa, M. (2008) ‘Advanced satellite technique for volcanic activity monitoring and early warning’. *Annals of Geophysics* 51 (1), 287-301

Pieri, D. and Abrams, M. (2005) ‘ASTER observations of thermal anomalies preceding the April 2003 eruption of Chikurachki volcano, Kurile Islands, Russia’. *Remote Sensing of Environment* 99, 84-94

Power, J. A.; Moran, S. C.; McNutt, S. R.; Stihler, S. D. and Sanchez, J. J. (2001) ‘Seismic Response of the Katmai Volcanoes to the 6 December 1999 Magnitude 7.0 Karluk Lake Earthquake, Alaska’. *Bulletin of the Seismological Society of America* 91 (1), 57-63

Pritchard, M. E. and Simons, M. (2004) ‘Surveying Volcanic Arcs with Satellite Radar Interferometry: The Central Andes, Kamchatka, and Beyond’. *GSA Today* 14 (8), 3-11

Pritchard, M. E.; Welch, M.; Jay, J. and Button, N. (2011) *A remote sensing assessment of the impact of the 2010 Maule, Chile earthquake (Mw 8.8) on the volcanoes of the southern Andes.* ‘American Geophysical Union Fall Meeting 2011’. held 3-9 December 2011 at San Francisco.

Rockstroh, E. (1903) ‘Recent earthquakes in Guatemala’. *Nature* 66, 150

Rothery, D. A.; Coppola, D. and Saunders, C. (2005) ‘Analysis of volcanic activity patterns using MODIS thermal alerts’. *Bulletin of Volcanology* 67 (6), 539-556

Selva, J.; Marzocchi, W.; Zencher, F.; Casarotti, E.; Piersanti, A. and Boschi, E. (2004) ‘A forward test for interaction between remote earthquakes and volcanic eruptions: the case of Sumatra (June 2000) and Denali (November 2002) earthquakes’. *Earth and Planetary Science Letters* 226, 383-395

Smithsonian Global Volcanism Program (2012) *Smithsonian Institution – Global Volcanism Program: Worldwide Holocene Volcano and Eruption Information* [online] available from < http://www.volcano.si.edu/index.cfm> [last accessed 18th July 2012]

Sparks, R. S. J. (2003) ‘Forecasting Volcanic Eruptions’. *Earth and Planetary Science Letters* 210, 1-15

Sparks, R. S. J. and Aspinall, W. P. (2004) ‘Volcanic Activity: Frontiers and Challenges in Forecasting, Prediction and Risk Assessment’. *The State of the Planet: Frontiers and Challenges in Geophysics* 19, 359-373

Stein, R. S. (1999) ‘The role of stress transfer in earthquake occurrence’. *Nature* 402, 605-609

Sturtevant, B.; Kanamori, H. and Brodsky, E. E. (1996) ‘Seismic triggering by rectified diffusion in geothermal systems’. *Journal of Geophysical Research* 101 (11), 25,269-25,282

Szakács, A. (2011) 'Earthquake prediction using extinct monogenetic volcanoes: A possible new research strategy'. *Journal of Volcanology and Geothermal Research* 201, 404-411

Thatcher, W. and Savage, J.C. (1982) 'Triggering of large earthquakesby magma-chamber inflation, Izu Peninsula, Japan'. *Geology* 10 (12), 637-640

Thorsteinsson, T.; Magnusson, B. and Gudjonsson, G. (2011) 'Large wildfire in Iceland in 2006: Size and intensity estimates from satellite data'. *International Journal of Remote Sensing* 32 (1-2), 17-29

Tokarev, P. I. (1971) 'Forecasting Volcanic Eruptions from Seismic Data'. *Bulletin Volcanologique* 35 (1), 243-250

Tralli, D.M.; Blom, R.G.; Zlotnicki, V.; Donnellan, A. and Evans, D.L. (2005) 'Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards'. *ISPRS Journal of Photogrammetry & Remote Sensing* 59, 185-198

Udias, A. (1999) *Principles of seismology.* Cambridge: Cambridge University Press

United Nations Environment Programme (UNEP) (2012) *Disasters and Conflicts: Introduction* [online] available from <http://www.unep.org/disastersandconflicts/Introduction/tabid/51921/Default.aspx> [17th May 2012]

United States Geological Survey (USGS) (2012a) *Earthquake Facts* [online] available from < http://earthquake.usgs.gov/learn/facts.php> [19th May 2012]

United States Geological Survey (USGS) (2012b) *Circular Area Earthquake Search* [online] available from < http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_circ.php> [last accessed 14th June 2012]

United States Geological Survey (USGS) (2012c) *What is Directivity?* [online] available from < http://earthquake.usgs.gov/regional/nca/rupture/directivity/> [18th July 2012]

USA Today (2012) *Mexico preps shelters as volcano roars, spews ash – USATODAY.com* [online] available from <http://www.usatoday.com/news/world/story/2012-04-20/Mexico-Volcano/54438738/1> [17th May 2012] van Manen, S. M.; Blake, S.; Dehn, J. and Valcic, L. (not published) 'Forecasting large explosions at Bezymianny volcano using thermal satellite data'. in *Remote Sensing of Volcanoes and Volcanic Processes: integration of observation and modelling.* ed. by Geological Society Special Publication

Vaughan, R. G. and Hook, S. J. (2006) 'Using satellite data to characterize the temporal behaviour of an active volcano: Mount St. Helens, WA'. *Geophysical Research Letters* 33, 1-4

Vaughan, R. G.; Kervyn, M.; Realmuto, V.; Abrams, M. and Hook, S. J. (2008) 'Satellite measurements of recent volcanic activity at Oldoinyo Lengai, Tanzania'. *Journal of Volcanology and Geothermal Research* 173, 196-206

Volcano Discover (2012) *Mexican earthquake might have triggered seismic swarm at San Salvador volcano, El Salvador* [online] available from < http://www.volcano discovery.com/san-salvador/news/7010/Mexican-earthquake-might-have-triggered-seismic-swarm-at-San-Salvador-volcano-El-Salvador.html> [17th May 2012]

Walter, T. R. (2007) 'How a tectonic earthquake may wake up volcanoes: Stress transfer during the 1996 earthquake-eruption sequence at the Karymsky Volcanic Group, Kamchatka'. *Earth and Planetary Science Letters* 264, 347-359

Walter, T. R. and Amelung, F. (2004) 'Influence of volcanic activity at Mauna Loa, Hawaii, on earthquake occurrence in the Kaoiki Seismic Zone'. *Geophysical Research Letters* 31, 1-4

Walter, T. R. and Amelung, F. (2006) 'Volcano-earthquake interaction at Mauna Loa volcano, Hawaii'. *Journal of Geophysical Research* 111, 1-17

Walter, T. R. and Amelung, F. (2007) 'Volcanic eruptions following M≥9 megathrust earthquakes: Implications for the Sumatra-Andaman volcanoes'. *Geology* 35 (6), 539-542

Walter, T. R.; Wang, R.; Zimmer, M.; Grosser, H.; Lühr, B. and Ratdomopurbo, A. (2007) 'Volcanic activity influenced by tectonic earthquakes: Static and dynamic stress triggering at Mt. Merapi'. *Geophysical Research Letters* 34, 1-5

Walter, T. R.; Wang, R.; Acocella, V.; Neri, M.; Grosser, H. and Zschau, J. (2009) ‘Simultaneous magma and gas eruptions at three volcanoes in southern Italy: an earthquake trigger?’. *Geology* 37 (3), 251-254

Walters, R. J.; Holley, R. J.; Parsons, B. and Wright, T. J. (2011) ‘Interseismic strain accumulation across the North Anatolian Fault from Envisat InSAR measurements’. *Geophysical Research Letters* 38, 1-5

Wang, P.; Liu, K. Y.; Cwik, T. and Green, R. (2002) ‘MODTRAN on supercomputers and parallel computers’. *Parallel Computing* 28, 53-64

Wang, F.; Shen, Z. K.; Wang, Y. Z. and Wang, M. (2011) ‘Influence of the March 11, 2011 M_w 9.0 Tohoku-oki earthquake on regional volcanic activities’. *Chinese Science Bulletin* 56 (20), 2077-2081

Watt, S. F. L.; Pyle, D. M. and Mather, T.A. (2009) ‘The influence of great earthquakes on volcanic eruption rate along the Chilean subduction zone’. *Earth and Planetary Science Letters* 277, 399-407

Webley, P. W.; Dehn, J.; Lovick, J.; Dean, K. G.; Bailey, J. E. and Valcic, L. (2009) ‘Near-real-time volcanic ash cloud detection: Experiences from the Alaska Volcano Observatory’. *Journal of Volcanology and Geothermal Research* 186, 79-90

Wells, D. L. and Coppersmith, K. J. (1994) ‘New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement’. *Bulletin of Seismological Society of America* 84 (4), 974-1002

West, M. L.; Sánchez, J.J. and McNutt, S. R. (2005) ‘Periodically Triggered Seismicity at Mount Wrangell, Alaska, After the Sumatra Earthquake’. *Science* 308, 1144-1146

Wiesnet, D. R. and D’Aguanno, J. (1982) ‘Thermal imagery of Mount Erebus from the NOAA-6 satellite’. *Antarctic Journal USA* 17, 32-34

Williams, R. S. and Friedman, J. D. (1970) ‘Satellite observation of effusive volcanism’. *Journal of the British Interplanetary Society* 23, 441-450

Wooster, M. (2007) ‘Remote sensing: sensors and systems’. *Progress in Physical Geography* 31 (1), 95-100

Wooster, M. J.; Zhukov, B. and Oertel, D. (2003) ‘Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products’. *Remote Sensing of Environment* 86, 83-107

Wooster, M. J.; Roberts, G.; Perry, G. L. W. and Kaufman, Y. J. (2005) ‘Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release’. *Journal of Geophysical Research* 110, 1-24

Wright, R.; Flynn, L.; Garbeil, H.; Harris, A. and Pilger, E. (2002) ‘Automated volcanic eruption detection using MODIS’. *Remote Sensing of Environment* 82, 135-155

Wright, R. and Flynn, L. P. (2003) ‘Satellite observations of thermal emission before, during, and after, the January 2003 eruption of Nyiragongo’. *Acta Vulcanologica* 15 (1-2), 67-74

Wright, R. and Flynn, L. P. (2004) ‘Space-based estimate of the volcanic heat flux into the atmosphere during 2001 and 2002’. *Geology* 32 (3), 189-192

Wright, R.; Flynn, L.; Garbeil, H.; Harris, A. and Pilger, E. (2004) ‘MODVOLC: near-real-time thermal monitoring of global volcanism’. *Journal of Volcanology and Geothermal Research* 135, 29-49

Wright, R.; Carn, S. A. and Flynn, L. P. (2005) ‘A satellite chronology of the May-June 2003 eruption of Anatahan volcano’. *Journal of Volcanology and Geothermal Research* 146, 102-116

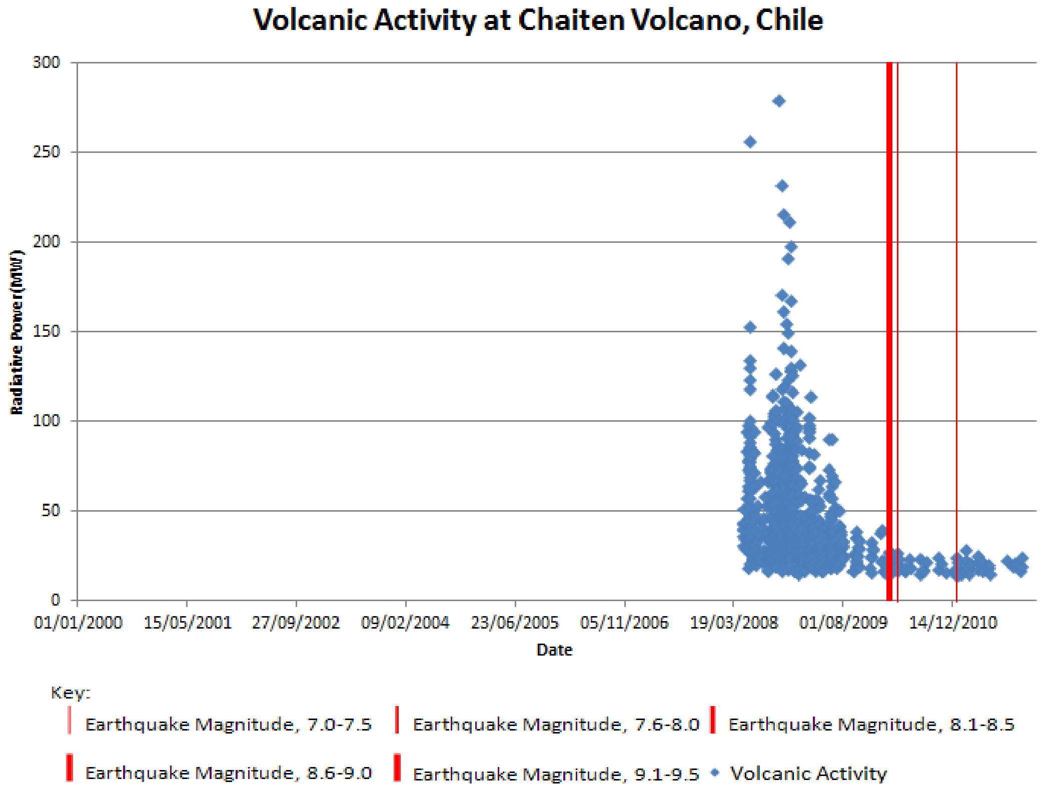
Wright, R. and Pilger, E. (2008) ‘Radiant flux from Earth’s subaerially erupting volcanoes’. *International Journal of Remote Sensing* 29 (22) 6443-6466

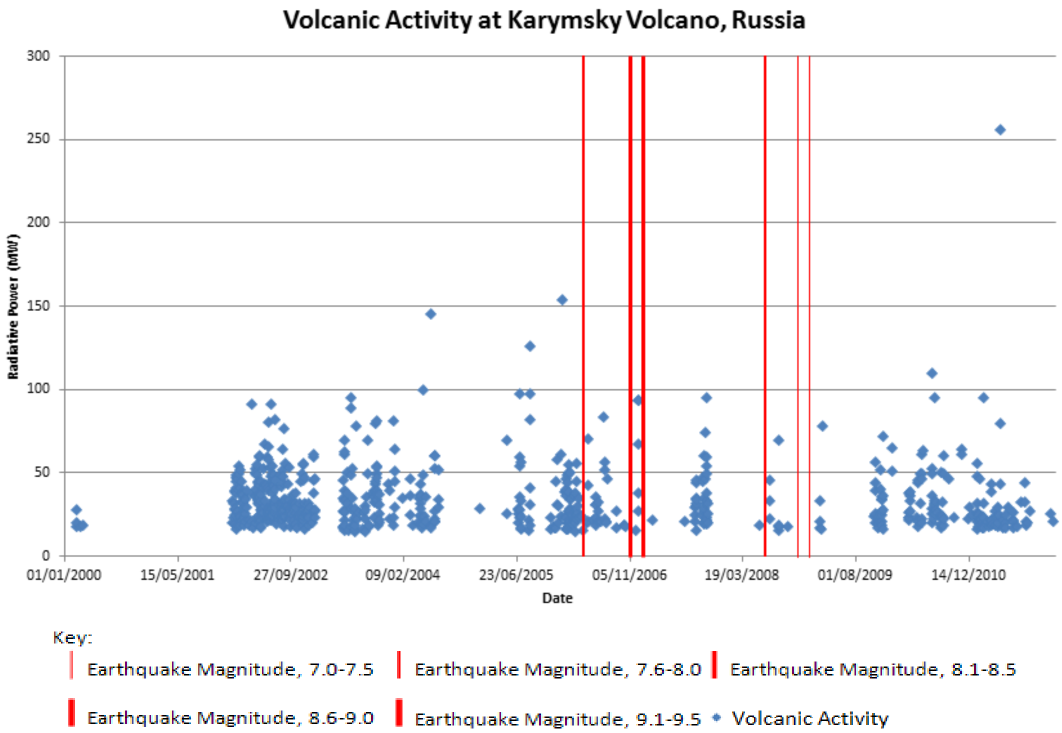
Yamazaki, K.; Teraishi, M.; Komatsu, S.; Sonoda, Y. and Kano, Y. (2011) ‘On the possibility of the 2011 Tohoku-oki earthquake reactivating Shinmoe-dake volcano, southwest Japan: insights from strain data measured in vaults’. *Natural Hazards and Earth System Sciences* 11, 2655-2661

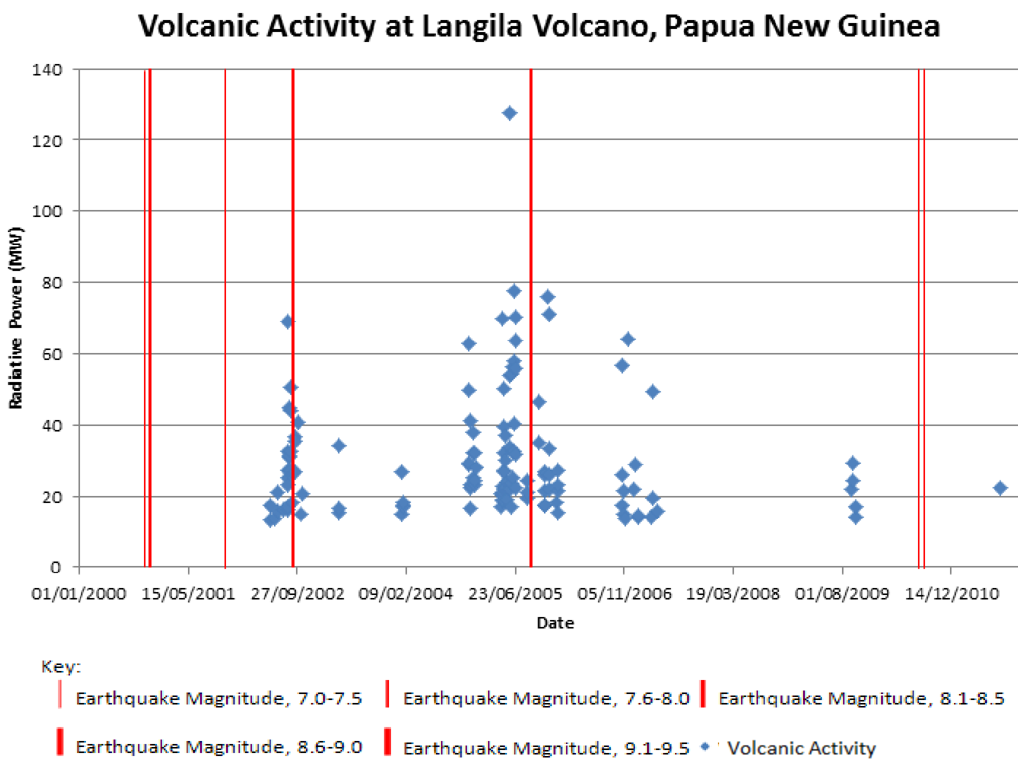
Zhuang, J. (2000) ‘Statistical modelling of seismicity patterns before and after the 1990 Oct 5 Cape Palliser earthquake, New Zealand’. *New Zealand Journal of Geology and Geophysics* 43, 447-460

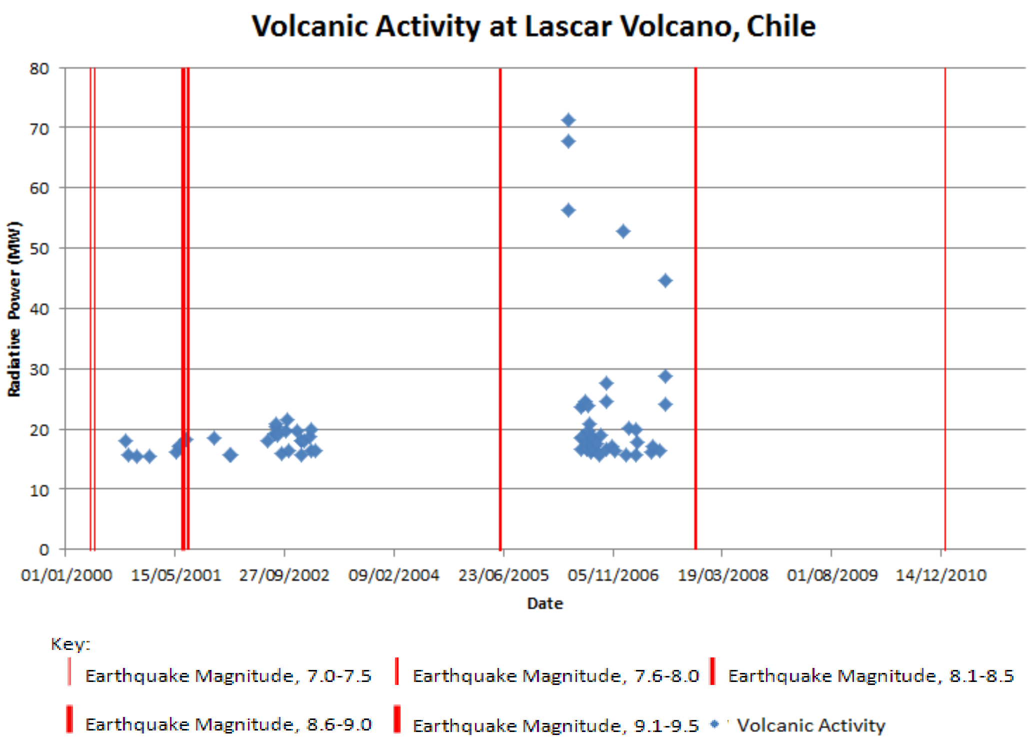
Appendix A

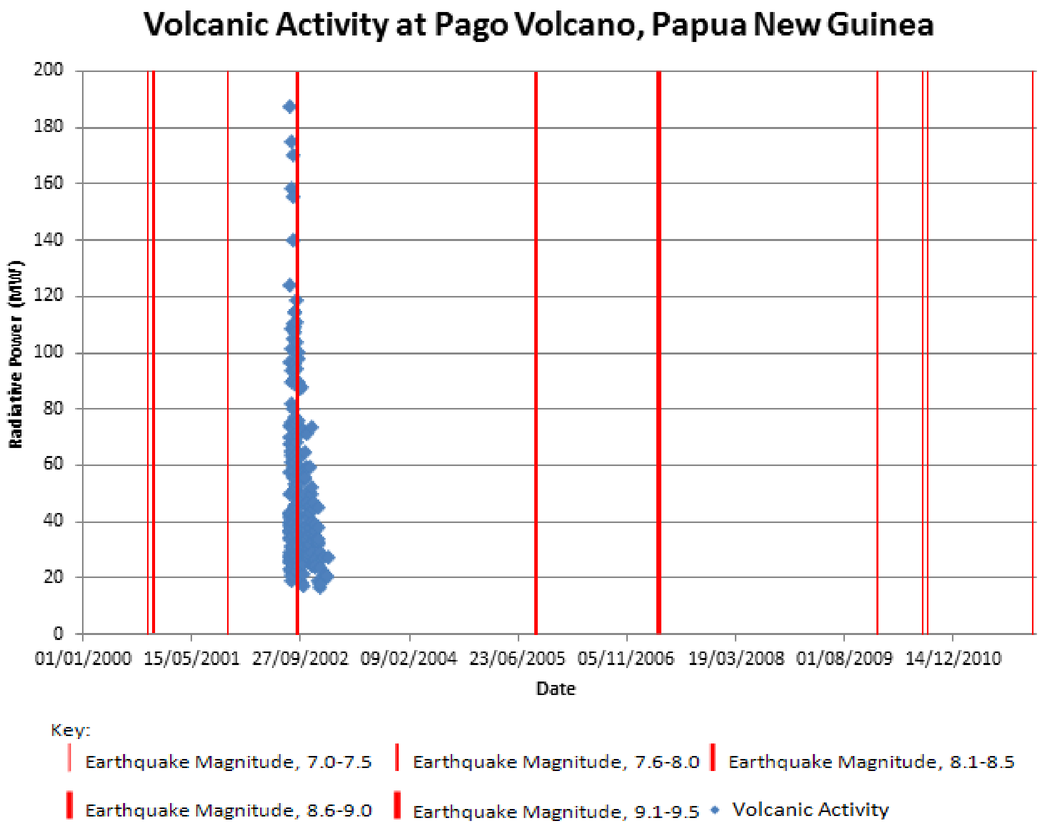
Volcanoes Identified for Further Analysis

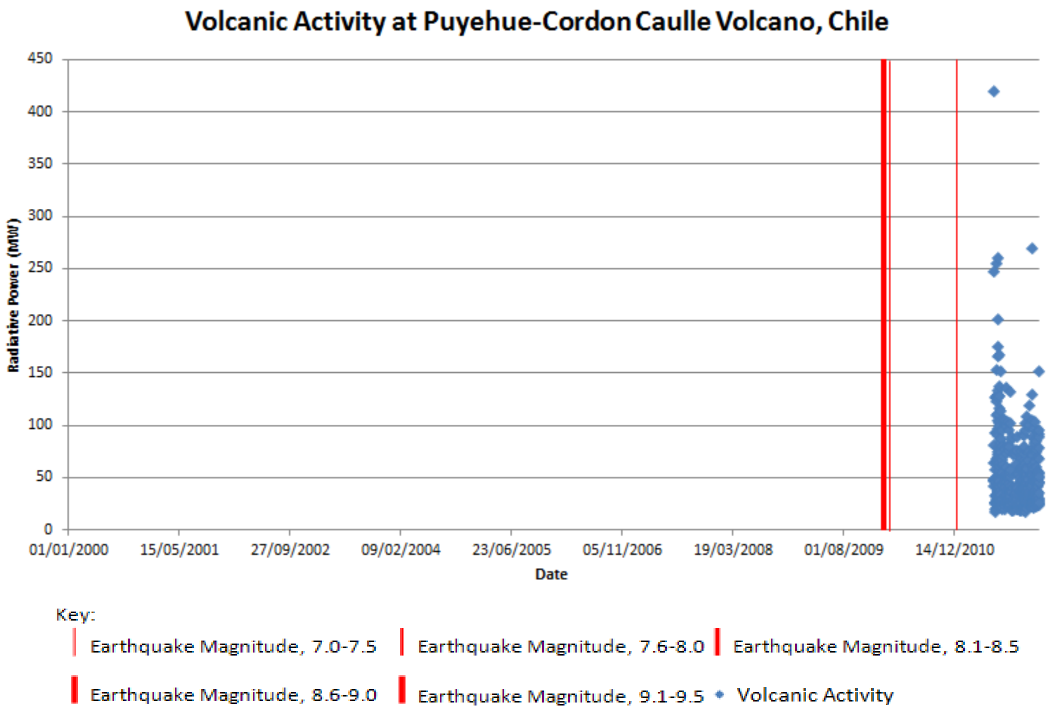


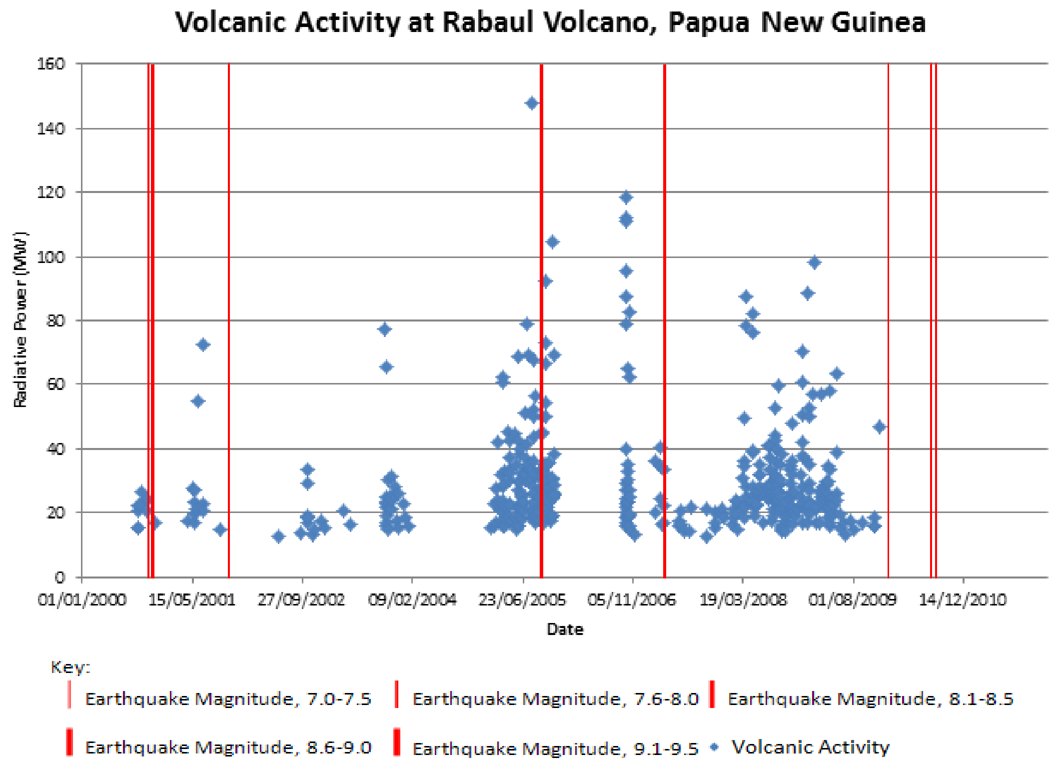


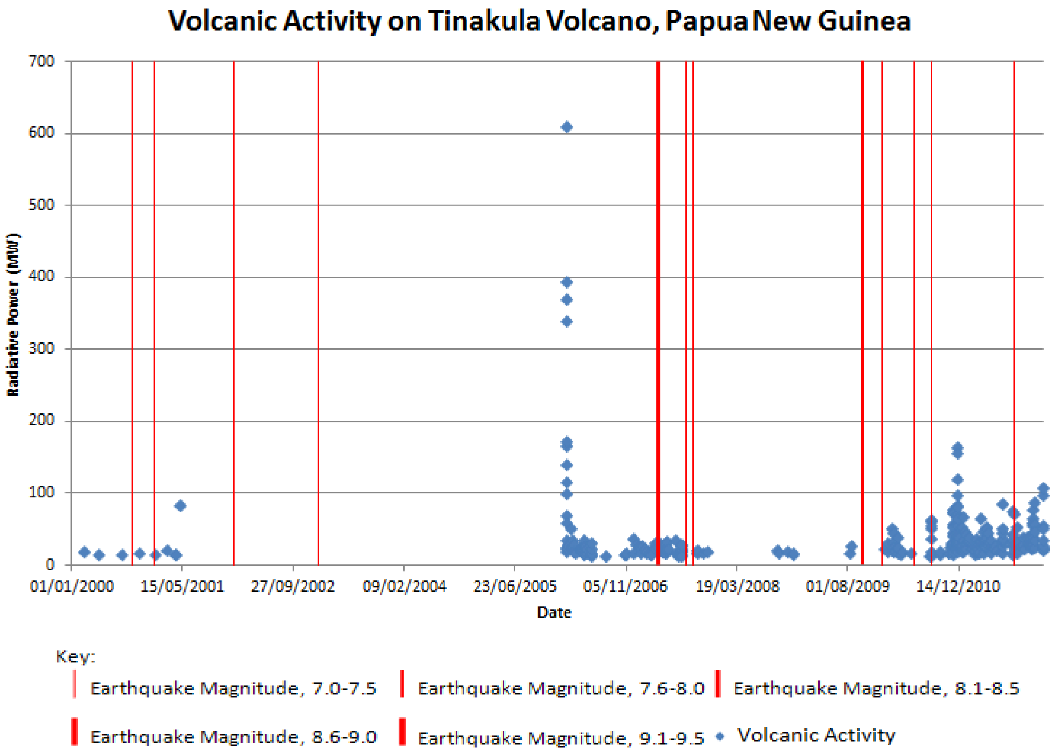

Volcanic Activity at Langila Volcano, Papua New Guinea
Radiative Power (MW)
140
120
100
80
60
40
20
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity


Volcanic Activity at Lascar Volcano, Chile
Radiative Power (MW)
80
70
60
50
40
30
20
10
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity


Volcanic Activity at Pago Volcano, Papua New Guinea
Radiative Power (MW)
200
180
160
140
120
100
80
60
40
20
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity


Volcanic Activity at Puyehue-Cordon Caulle Volcano, Chile
Radiative Power (MW)
450
400
350
300
250
200
150
100
50
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity


Volcanic Activity at Rabaul Volcano, Papua New Guinea
Radiative Power (MW)
160
140
120
100
80
60
40
20
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity


Volcanic Activity on Tinakula Volcano, Papua New Guinea
Radiative Power (MW)
700
600
500
400
300
200
100
0
01/01/2000
15/05/2001
27/09/2002
09/02/2004
23/06/2005
05/11/2006
19/03/2008
01/08/2009
14/12/2010
Date
Key:
Earthquake Magnitude, 7.0-7.5
Earthquake Magnitude, 7.6-8.0
Earthquake Magnitude, 8.1-8.5
Earthquake Magnitude, 8.6-9.0
Earthquake Magnitude, 9.1-9.5
Volcanic Activity

Appendix B

Global seismic activity data for all earthquakes M≥6.0 examined in this thesis, obtained from USGS NEIC

Date	Time (hhmmss.mm) UTC	Latitude	Longitude	Magnitude	Depth (km)
08/01/2000	11946.66	-9.805	159.811	6.4	33
06/02/2000	113352.28	-5.844	150.876	6.6	33
03/03/2000	222240.74	-6.817	143.807	6.6	10
08/05/2000	102825.22	-4.457	150.004	6.1	502
09/06/2000	12715.16	-5.071	152.495	6.3	33
09/06/2000	84159.74	-11.301	162.062	6.1	33
16/06/2000	75535.39	-33.877	-70.088	6.4	120
16/07/2000	35745.56	-7.747	150.917	6.4	10
14/08/2000	221116.11	-9.377	153.854	6.0	10
29/10/2000	83708.77	-4.766	153.945	7.0	50
07/11/2000	10149.26	-5.538	151.592	6.0	33
07/11/2000	75009.67	-5.432	154.016	6.2	90
16/11/2000	45456.74	-3.98	152.169	8.0	33
16/11/2000	52122.41	-5.069	153.238	6.0	33
16/11/2000	74216.93	-5.233	153.102	7.8	30
16/11/2000	74532.94	-4.827	153.226	6.5	33
16/11/2000	110541.64	-5.29	152.968	6.2	33
17/11/2000	210156.49	-5.496	151.781	7.8	33
18/11/2000	20548.81	-5.097	153.181	6.6	33
18/11/2000	65458.35	-5.228	151.771	6.8	33
18/11/2000	230539.78	-5.384	153.452	6.1	33
19/11/2000	24527.57	-5.133	151.655	6.0	57
19/11/2000	53519.3	-5.588	151.867	6.1	33
21/11/2000	173334.45	-5.486	152.153	6.2	33
21/11/2000	212105.26	-5.43	152.688	6.1	33
23/11/2000	184315.66	-4.585	153.058	6.3	33
06/12/2000	225740.04	-4.218	152.725	6.5	31
20/12/2000	112354.1	-39.008	-74.662	6.5	11
20/12/2000	164943.3	-9.231	154.353	6.6	33
21/12/2000	10127.77	-5.706	151.122	6.4	33
21/12/2000	24123.13	-5.354	154.133	6.0	386
28/12/2000	43428.45	-4.05	152.307	6.2	33
02/01/2001	231741.97	-11.16	162.44	6.0	33
15/03/2001	130242.11	-32.321	-71.492	6.0	37
09/04/2001	90057.17	-32.668	-73.109	6.7	11
19/04/2001	31325.58	-7.455	155.893	6.0	12
19/04/2001	205826.14	-7.306	155.965	6.2	20
19/04/2001	214342.28	-7.41	155.865	6.7	17
09/05/2001	173826.12	-10.318	161.232	6.3	67
29/05/2001	233719.49	-7.022	155.037	6.4	14
05/06/2001	90005.38	-6.884	146.388	6.4	10

05/06/2001	151358.15	-6.815	146.41	6.0	10
01/07/2001	14606.13	-4.312	152.956	6.1	28
08/07/2001	175418.76	-6.663	152.108	6.2	10
02/08/2001	234106.17	56.26	163.79	6.3	14
23/08/2001	214503.16	-3.373	146.311	6.2	10
07/10/2001	22109.81	-3.296	142.934	6.2	10
08/10/2001	181426.44	52.591	160.324	6.5	48
08/10/2001	182038.25	52.631	160.214	6.4	33
31/10/2001	91020	-5.912	150.196	7.0	33
13/11/2001	104323.08	53.627	170.551	6.0	33
23/12/2001	225254.33	-9.613	159.53	6.8	16
10/01/2002	111456.93	-3.212	142.427	6.7	11
13/01/2002	141056.52	-5.651	151.074	6.4	43
15/01/2002	90115.95	-5.527	151.097	6.2	41
28/01/2002	135028.72	49.381	155.594	6.1	33
30/01/2002	125819.22	-6.252	150.887	6.0	33
05/02/2002	132724.67	-5.345	151.248	6.6	39
19/02/2002	3545.7	-3.731	150.992	6.1	10
28/02/2002	15048.94	-5.685	151.258	6.3	40
23/05/2002	155215.28	-30.749	-71.197	6.0	52
06/06/2002	235348.47	-0.879	148.33	6.3	10
18/06/2002	135622.83	-30.805	-71.124	6.6	54
21/06/2002	544.85	-4.495	146.768	6.0	33
03/07/2002	230018.47	-5.032	147.336	6.2	31
08/09/2002	184423.71	-3.302	142.945	7.6	13
16/09/2002	132300.99	-3.313	142.679	6.3	10
17/09/2002	112023.39	-3.284	142.769	6.0	10
24/09/2002	35722.28	-31.519	-69.2	6.3	119
24/09/2002	41311.63	-10.535	161.2	6.1	10
24/09/2002	225421.48	-10.565	161.11	6.3	10
24/09/2002	230128.67	-10.65	161.21	6.3	19
16/10/2002	101221.43	51.952	157.323	6.2	102
17/10/2002	175244.19	-3.597	140.226	6.3	33
19/10/2002	4356.43	-3.667	140.312	6.0	33
31/10/2002	13516.67	-3.441	148.638	6.1	10
12/12/2002	83042.77	-4.786	153.275	6.7	34
20/12/2002	141442.05	-3.076	147.943	6.3	33
10/01/2003	131156.91	-5.311	153.701	6.7	71
20/01/2003	84306.07	-10.491	160.77	7.3	33
10/02/2003	44931.12	-6.011	149.792	6.3	33
12/02/2003	223330.83	-3.652	144.242	6.2	10
11/03/2003	72732.65	-4.694	153.238	6.8	40
15/03/2003	194128.7	52.249	160.387	6.1	30
19/03/2003	342.92	-9.388	156.587	6.2	33
31/03/2003	10653.05	-6.183	151.429	6.2	46
24/04/2003	105621.98	48.764	154.991	6.1	43
07/06/2003	3245.57	-5.095	152.502	6.6	33
12/06/2003	85920.24	-5.985	154.758	6.3	186
16/06/2003	220802.14	55.492	159.999	6.9	174
20/06/2003	133041.64	-30.608	-71.637	6.8	33

28/06/2003	152942.26	-3.325	146.148	6.3	10
04/07/2003	3350.04	-5.473	151.691	6.1	10
15/07/2003	184638.12	-3.828	152.174	6.5	33
21/07/2003	135358.49	-5.481	148.853	6.4	189
25/07/2003	93745.84	-1.528	149.694	6.4	24
11/09/2003	215825.55	-8.205	156.159	6.0	10
12/09/2003	65555.8	-5.273	151.502	6.0	50
17/10/2003	101906.82	-5.471	154.155	6.4	133
22/10/2003	114530.84	-6.058	147.727	6.3	53
28/10/2003	23351.52	-5.376	151.509	6.0	65
25/11/2003	201946.29	-5.581	150.88	6.6	35
05/12/2003	212609.48	55.538	165.78	6.7	10
09/01/2004	223531.19	-6.072	149.401	6.3	57
15/01/2004	72653.01	-3.528	151.064	6.2	10
11/04/2004	73729.85	-3.729	140.081	6.2	20
14/04/2004	15409.22	55.226	162.659	6.2	51
22/04/2004	141607	-3.355	146.853	6.0	35
03/05/2004	43650.04	-37.695	-73.406	6.6	21
13/05/2004	95843.45	-3.584	150.73	6.4	10
10/06/2004	151957.75	55.682	160.003	6.9	188
15/06/2004	111631.5	-38.854	-73.155	6.1	37
08/07/2004	103049.16	47.198	151.303	6.4	128
28/08/2004	134125.6	-35.173	-70.525	6.5	5
19/09/2004	202604.1	52.205	174.027	6.2	25
08/10/2004	82753.54	-10.951	162.161	6.8	36
05/11/2004	51835.05	-4.361	143.925	6.0	125
11/11/2004	173452.05	-11.128	162.208	6.7	10
16/11/2004	100654.5	-5.627	151.452	6.1	55
18/12/2004	64619.87	48.837	156.309	6.2	11
14/01/2005	83314.46	-4.238	152.717	6.1	10
22/01/2005	203017.35	-7.727	159.475	6.4	29
07/02/2005	200217.69	-4.525	153.187	6.1	36
23/02/2005	113352.9	-6.245	150.66	6.0	10
11/04/2005	122005.96	-3.484	145.909	6.6	11
04/06/2005	145046.65	-6.319	146.846	6.1	26
15/06/2005	101359.39	-4.595	153.191	6.2	74
15/06/2005	195224.82	-44.865	-80.562	6.4	10
09/09/2005	72643.73	-4.539	153.474	7.6	90
29/09/2005	155024.03	-5.437	151.84	6.6	25
29/09/2005	182325.98	-5.563	151.865	6.2	28
15/10/2005	100617.01	46.816	154.113	6.1	42
05/11/2005	104821.22	-3.149	148.143	6.4	25
22/11/2005	151131.58	-5.154	145.284	6.2	68
08/12/2005	90127.11	-5.408	146.953	6.1	216
11/12/2005	142045	-6.584	152.223	6.6	17
18/02/2006	155922.09	-5.193	152.053	6.2	44
24/03/2006	122705.38	-3.245	143.144	6.1	12
12/04/2006	10658.69	56.397	163.99	6.0	28
20/04/2006	232502.15	60.949	167.089	7.6	22
21/04/2006	43243.82	60.527	165.816	6.1	9

21/04/2006	111415.33	61.354	167.525	6.1	12
29/04/2006	165806.32	60.491	167.516	6.6	11
22/05/2006	111200.8	60.772	165.743	6.6	19
22/05/2006	130802.95	54.271	158.447	6.2	197
28/05/2006	31208.76	-5.724	151.133	6.5	34
19/07/2006	114858.29	-5.474	150.684	6.4	28
20/08/2006	30102.41	49.823	156.415	6.0	26
24/08/2006	215036.65	51.148	157.522	6.5	43
01/09/2006	101851.6	-6.759	155.512	6.8	38
17/09/2006	93413.58	-31.733	-67.145	6.2	137
30/09/2006	175023.05	46.351	153.166	6.6	11
01/10/2006	90602.32	46.47	153.24	6.5	19
12/10/2006	180556.57	-31.256	-71.368	6.4	31
17/10/2006	12512.23	-5.881	150.982	6.7	32
06/11/2006	205651.11	-5.45	146.637	6.0	133
07/11/2006	173833.8	-6.482	151.195	6.6	11
12/11/2006	182126.14	-6.225	151.05	6.2	12
13/11/2006	161228.98	-6.38	151.23	6.2	11
15/11/2006	111413.57	46.592	153.266	8.3	10
15/11/2006	112509	47.518	152.647	6.0	10
15/11/2006	112838.46	46.086	154.1	6.0	10
15/11/2006	112922.79	46.371	154.475	6.2	10
15/11/2006	113458.13	46.652	155.305	6.4	10
15/11/2006	114055.05	46.483	154.726	6.7	10
15/11/2006	192525.99	47.006	154.979	6.0	10
16/11/2006	62020.77	46.358	154.468	6.0	9
07/12/2006	191021.85	46.153	154.386	6.4	16
26/12/2006	151945.21	48.321	154.837	6.0	10
27/12/2006	201538.64	-5.724	154.424	6.0	355
13/01/2007	42321.16	46.243	154.524	8.1	10
13/01/2007	173706.31	46.913	156.276	6.0	10
17/01/2007	42826.66	-3.322	139.834	6.0	100
01/04/2007	203958.71	-8.466	157.043	8.1	24
01/04/2007	204619.35	-9.505	156.934	6.1	24
01/04/2007	204731.31	-7.169	155.777	6.6	10
01/04/2007	211133.15	-7.306	155.741	6.9	10
01/04/2007	211522.7	-7.303	155.682	6.0	10
02/04/2007	24935.9	-45.382	-73.058	6.1	4
02/04/2007	104917.72	-7.225	156.243	6.1	34
02/04/2007	120223.34	-8.706	157.62	6.2	14
02/04/2007	232023.27	-8.617	157.386	6.2	18
03/04/2007	120427.37	-7.857	155.801	6.1	8
04/04/2007	3943.95	-7.141	156.047	6.0	10
04/04/2007	63435.96	-7.76	156.49	6.4	17
21/04/2007	71248.06	-3.548	151.266	6.1	407
21/04/2007	175346.31	-45.243	-72.648	6.2	36
07/05/2007	111516.23	-44.85	-80.453	6.1	10
29/05/2007	10327.92	-4.587	151.841	6.1	132
30/05/2007	202212.66	52.137	157.293	6.4	116
07/06/2007	4038.13	-3.316	146.761	6.2	4

18/06/2007	61845.68	-3.55	150.962	6.3	9
28/06/2007	25210.99	-7.979	154.635	6.7	18
16/08/2007	83928.44	-9.834	159.465	6.5	15
26/09/2007	123626.89	-4.99	153.5	6.8	40
09/10/2007	150341.21	-4.808	152.892	6.0	39
21/10/2007	102452.06	-6.31	154.77	6.0	46
25/10/2007	135004.26	46.011	154.231	6.1	20
20/11/2007	125259.03	-6.907	155.672	6.0	52
22/11/2007	84827.53	-5.757	147.098	6.8	53
27/11/2007	114958.01	-10.95	162.149	6.6	16
01/01/2008	185459.01	-5.878	146.884	6.3	34
03/03/2008	93102.5	46.406	153.175	6.5	10
03/06/2008	162050.38	-10.509	161.273	6.2	84
05/07/2008	21204.48	53.882	152.886	7.7	632
24/07/2008	14316.14	50.967	157.584	6.2	27
28/07/2008	214047.36	-10.578	163.103	6.0	10
30/08/2008	65407.61	-6.146	147.258	6.4	75
23/10/2008	100435.04	-2.635	145.574	6.3	10
28/10/2008	160003.24	-3.494	145.867	6.0	18
01/11/2008	11309.64	-3.399	148.712	6.0	10
21/11/2008	70534.94	-8.947	159.553	6.1	118
24/11/2008	90258.76	54.203	154.322	7.3	492
18/12/2008	211928.38	-32.458	-71.726	6.2	18
18/12/2008	215028	-32.473	-72.051	6.0	25
15/01/2009	174939.07	46.857	155.154	7.4	36
22/01/2009	134025.99	-5.912	148.511	6.1	44
01/04/2009	35458.77	-3.522	144.102	6.4	10
21/04/2009	52611.52	50.833	155.009	6.2	152
12/05/2009	12626.58	-5.664	149.543	6.1	89
23/06/2009	141922.35	-5.157	153.782	6.7	64
15/07/2009	201042.66	-3.375	150.506	6.1	13
10/09/2009	24650.35	48.317	154.192	6.0	36
10/10/2009	212438.53	47.851	152.455	6.0	112
10/12/2009	23052.69	53.417	152.756	6.3	656
14/12/2009	85401.82	-5.958	154.444	6.0	39
03/01/2010	214802.87	-8.726	157.487	6.6	10
03/01/2010	223625.64	-8.783	157.354	7.1	10
05/01/2010	121532.21	-9.019	157.551	6.8	15
05/01/2010	131142.82	-9.05	157.892	6.0	35
09/01/2010	55130.47	-9.131	157.626	6.2	12
01/02/2010	222816.92	-6.112	154.463	6.2	32
06/02/2010	44458.4	46.836	152.731	6.0	30
27/02/2010	63411.53	-36.122	-72.898	8.8	22
27/02/2010	65117.65	-31.663	-69.141	6.0	39
27/02/2010	65234.02	-34.867	-72.614	6.2	35
27/02/2010	71228.45	-33.878	-71.943	6.0	35
27/02/2010	73717.96	-36.869	-72.673	6.0	35
27/02/2010	80123.01	-37.773	-75.048	7.4	35
27/02/2010	82529.62	-34.749	-72.427	6.1	35
27/02/2010	103036.4	-33.281	-71.955	6.0	35

27/02/2010	172430.59	-36.354	-73.208	6.1	19
27/02/2010	190006.86	-33.422	-71.828	6.2	31
27/02/2010	231234.91	-34.7	-71.827	6.0	35
28/02/2010	112535.92	-34.903	-71.617	6.2	46
03/03/2010	174425.04	-36.61	-73.36	6.1	20
04/03/2010	15948.67	-33.216	-72.125	6.0	24
05/03/2010	91936.38	-36.631	-73.223	6.1	29
05/03/2010	114706.82	-36.665	-73.374	6.6	18
11/03/2010	143943.95	-34.29	-71.891	6.9	11
11/03/2010	145527.51	-34.326	-71.799	7.0	18
11/03/2010	150602.13	-34.47	-72.004	6.0	31
15/03/2010	110828.96	-35.802	-73.158	6.2	14
16/03/2010	22157.94	-36.217	-73.257	6.7	18
20/03/2010	140049.98	-3.361	152.245	6.6	414
28/03/2010	213828	-35.387	-73.385	6.0	29
02/04/2010	225807.56	-36.227	-72.878	6.0	24
07/04/2010	143301.93	-3.76	141.943	6.0	23
11/04/2010	94025.6	-10.878	161.116	6.9	21
17/04/2010	231522.02	-6.669	147.291	6.2	53
23/04/2010	100306.18	-37.529	-72.969	6.0	32
03/05/2010	230944.79	-38.072	-73.454	6.3	19
24/06/2010	53227.4	-5.514	151.161	6.1	40
26/06/2010	53019.49	-10.627	161.447	6.7	35
14/07/2010	83221.49	-38.067	-73.31	6.6	22
18/07/2010	130409.41	-5.966	150.428	6.9	28
18/07/2010	133459.36	-5.931	150.59	7.3	35
20/07/2010	191820.37	-5.902	150.712	6.3	24
30/07/2010	35613.71	52.498	159.843	6.3	23
04/08/2010	71533.51	-5.486	146.822	6.5	220
04/08/2010	220143.62	-5.746	150.765	7.0	44
15/08/2010	150929.24	-5.692	148.342	6.3	174
20/08/2010	175614.15	-6.57	154.246	6.1	19
09/09/2010	72801.72	-37.034	-73.412	6.2	16
23/11/2010	90106.86	-5.959	148.966	6.1	68
02/12/2010	31209.82	-6.001	149.977	6.6	33
13/12/2010	11442.32	-6.534	155.647	6.2	135
23/12/2010	140032.33	53.127	171.161	6.3	18
02/01/2011	202017.78	-38.355	-73.326	7.2	24
07/02/2011	195344.16	-7.161	155.175	6.4	428
11/02/2011	200530.79	-36.474	-73.125	6.9	27
12/02/2011	11701.41	-37.027	-72.954	6.1	16
13/02/2011	103506.74	-36.649	-73.176	6.0	17
14/02/2011	34009.92	-35.38	-72.834	6.7	21
20/02/2011	214324.15	55.918	162.117	6.1	33
07/03/2011	936.45	-10.349	160.766	6.3	22
09/03/2011	212449.76	-5.985	149.777	6.4	29
23/04/2011	41654.72	-10.375	161.2	6.8	79
15/05/2011	183710.37	-6.104	154.414	6.4	40
01/06/2011	125522.38	-37.578	-73.691	6.3	21
16/06/2011	335.79	-5.928	151.04	6.4	16

16/07/2011	2612.64	-33.819	-71.832	6.0	20
20/07/2011	220459.32	-10.34	162.01	6.0	21
25/07/2011	5047.59	-3.182	150.611	6.3	10
31/07/2011	233856.61	-3.518	144.828	6.6	10
04/08/2011	135134.56	48.833	154.769	6.1	36
14/09/2011	181009	53.107	172.984	6.0	15
14/10/2011	33514.81	-6.57	147.881	6.5	37
18/10/2011	50506.25	-5.785	151.037	6.1	26
28/11/2011	122645.45	-5.48	153.733	6.1	25
14/12/2011	50459.27	-7.561	146.804	7.1	140

Appendix C

Ethical Approval

Project Information

Project Ref: **P1468**

Full name: Charley Hill-Butler

Faculty: [BES] Business, Environment and Society

Department: [BESA1G] BES Geography, Environment and Disaster Management

Module Code:

Supervisor: Matthew Blackett

Project title: **A Spatial and Statistical Analysis of the Relationship between Earthquakes and Volcanic Activity.**

Date(s): 26/09/2011

Created: 10/10/2011 11:06

Project Information:

Participants in your research		
1	Will the project involve human participants?	No

Risk to Participants		
1	Will the project involve human patients/clients, health professionals, and/or patient (client) data and/or health professional data?	No
2	Will any invasive physical procedure, including collecting tissue or other samples, be used in the research?	No
3	Is there a risk of physical discomfort to those taking part?	No
4	Is there a risk of psychological or emotional distress to those taking part?	No
5	Is there a risk of challenging the deeply held beliefs of those taking part?	No
6	Is there a risk that previous, current or proposed criminal or illegal acts will be revealed by those taking part?	No
7	Will the project involve giving any form of professional, medical or legal advice, either directly or indirectly to those taking part?	No

Risk to Researcher		
1	Will this project put you or others at risk of physical harm, injury or death?	No
2	Will project put you or others at risk of abduction, physical, mental or sexual abuse?	No
3	Will this project involve participating in acts that may cause psychological or emotional distress to you or to others?	No

Risk to Researcher		
4	Will this project involve observing acts which may cause psychological or emotional distress to you or to others?	No
5	Will this project involve reading about, listening to or viewing materials that may cause psychological or emotional distress to you or to others?	No
6	Will this project involve you disclosing personal data to the participants other than your name and the University as your contact and e-mail address?	No
7	Will this project involve you in unsupervised private discussion with people who are not already known to you?	No
8	Will this project potentially place you in the situation where you may receive unwelcome media attention?	No
9	Could the topic or results of this project be seen as illegal or attract the attention of the security services or other agencies?	No
10	Could the topic or results of this project be viewed as controversial by anyone?	No
11	Does the project involve the researcher travelling outside the UK?	No

Informed Consent of the Participant		
1	Are any of the participants under the age of 18?	No
2	Are any of the participants unable mentally or physically to give consent?	No
3	Do you intend to observe the activities of individuals or groups without their knowledge and/or informed consent from each participant (or from his or her parent or guardian)?	No

Participant Confidentiality and Data Protection		
1	Will the project involve collecting data and information from human participants who will be identifiable in the final report?	No
2	Will information not already in the public domain about specific individuals or institutions be identifiable through data published or otherwise made available?	No
3	Do you intend to record, photograph or film individuals or groups without their knowledge or informed consent?	No
4	Do you intend to use the confidential information, knowledge or trade secrets gathered for any purpose other than this research project?	No

Gatekeeper Protection		
1	Will this project involve collecting data outside University buildings?	No
2	Do you intend to collect data in shopping centres or other public places?	No
3	Do you intend to gather data within nurseries, schools or colleges?	No
4	Do you intend to gather data within National Health Service premises?	No

Other Ethical Issues		
1	Is there any other risk or issue not covered above that may pose a risk to you or any of the participants?	No
2	Will any activity associated with this project put you or the participants at an ethical, moral or legal risk?	No

Principal Investigator's Declaration	
I believe that this project **does not require research ethics approval**. I have completed the checklist and kept a copy for my own records. I realise I may be asked to provide a copy of this checklist at any time.	Yes
I confirm that I have answered all relevant questions in this checklist honestly.	Yes
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request a new ethical approval if the project subsequently changes the information I have given in this checklist.	Yes

Attachments	
Participant Information Leaflet.	-
Informed Consent Form.	-
Health & Safety Assessment attached.	-

Step	Status	Authoriser	Authorised on
Supervisor	Approved	Matthew Blackett	Mon, 10 Oct 2011 12:33 PM
Referrer	Not required		